Master's Thesis

Microstrip Ring Resonator for Noninvasive and Continuous Glucose Monitoring System

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Abstract

Noninvasive glucose monitoring system has been a scrumptious field of research for last three decades. With the advancement of technology and equipment, many non-invasive glucose monitoring devices have been evolved. Some of them are promising technology among the others. However, several published researches hide much of the research data. Even many of them do not have new updates afterwards their promising approach. Moreover, limitations and negative reviews regarding the glucose monitoring devices available in the market, have been reported. Thus, the search for the next generation of pain free, reliable, cost effective glucose monitoring technique is still alive. Researchers are now more interested in the study of microwave or electromagnetic sensing technique in the industrial, scientific and medical (ISM) radio frequency bands which detects the dielectric parameters of the blood and interstitial fluid, caused by the changes in glucose concentration level as a possible approach for non-invasive and continuous blood glucose monitoring. In recent years there are reports of ring resonators and split ring resonators being studied as glucose sensor. However, these reports also suffer from accuracy problem, complex and incompatible circuitry problem. It is a challenge to detect the change in the glucose concentration level that a human body requires. In this work, we intend to investigate the feasibility of microstrip ring resonator for sensing the change in aqueous glucose concentration level in the range that human body allows. It is designed to operate within 2 GHz range which is compatible with circuit integration. S_{21} parameter is being observed for different glucose concentrations. As the dielectric constant changes, the resonant frequency shifts. The new sensor shows sensitivity of 3 MHz per 100 mg/dl. Further research on the proposed model can be conducted to make it flexible for using it on human arm for noninvasive and continuous glucose monitoring.

Key Words — Continuous glucose monitoring, Noninvasive glucose monitoring, Blood glucose, microwave sensor, ring resonator, interstitial fluid.

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Nomenclature

CGM	Continuous Blood Glucose Monitoring
ISF	Interstitial Fluid
ISM	Industrial Scientific Medical radio band
BG	Blood Glucose
GL	Glucose Level
NGM	Non-invasive glucose Monitoring
CGM	Continuous Blood Glucose Monitoring
NIBGM	Non-invasive Blood Glucose Monitoring
FDA	Food and Drug Administration

Chapter 1

Introduction

Millions of diabetes patients every day feel hustle to monitor their blood glucose level and keep fit. Blood glucose meters based on finger pricking has become painful for regular testing of blood sugar level. Addressing the daily problem of the patients, researches have been conducted for past two decades for noninvasive methods of monitoring glucose level in the human body. Over the past fifty years the microwave technique has been used increasingly in a wide range of sensing applications. Microwave sensors possess the ability of measuring in sensitive environments where direct contact with the sample cannot be achieved. This property suggests that microwave sensors are well suited for noninvasive, nondestructive and continuous monitoring of blood glucose concentration. Unfortunately, most of the methods currently used for measuring blood glucose level, are invasive or minimally invasive, requiring direct contact with a sample of blood. The intent of this thesis is to outline the design of a microwave sensor that can be applied to noninvasive monitoring of blood glucose level.

1.1 Diabetes

Diabetes is a disease that is caused by the imbalance of blood glucose level in our body. Insulin, a major hormone in our body, originates from pancreases and is responsible for keeping a balance of glucose level in our body. When the body is cannot produce or use insulin properly, there is imbalance in the blood glucose level which leads to diabetes [1.1]. It has become a worldwide problem. Millions of people are suffering from diabetes all over the globe and the number is still increasing day by day [1.2].

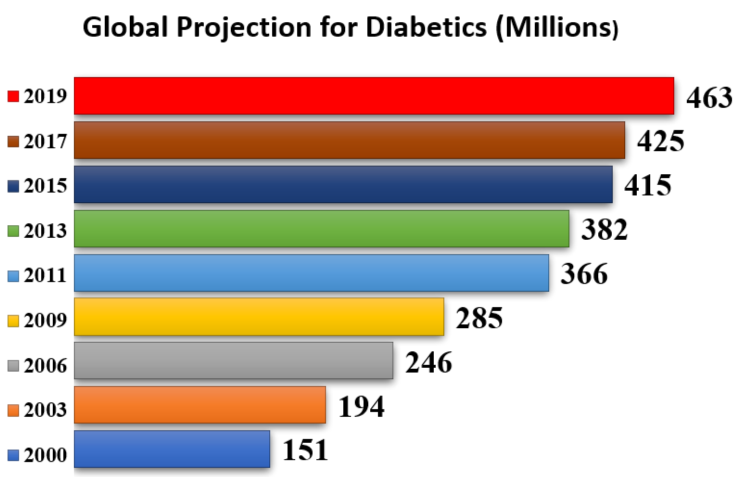


Figure 1-1. Global projection for diabetics (Data Source: International Diabetes Federation)

1.2 Types of Diabetes

Insulin balances the high blood glucose level in our body. When the glucose level rises pancreas secretes insulin. Insulin carries sugar to the cells and carries the extra sugar to the liver and stores it as glycogen for future use.

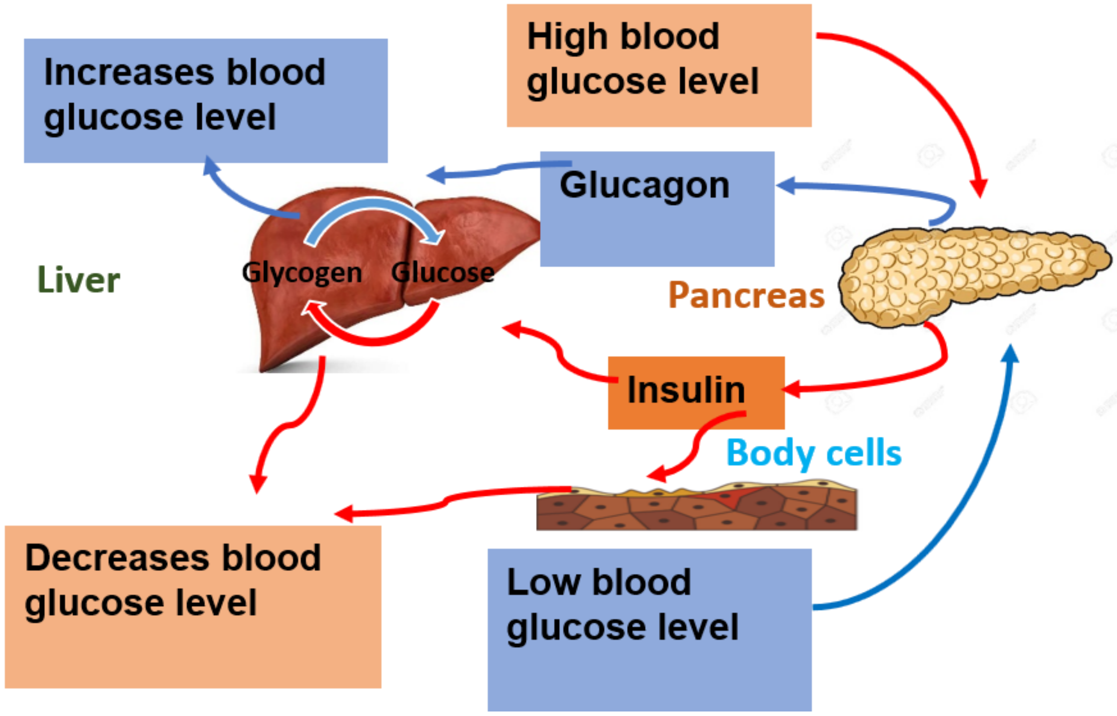


Figure 1-2. How Insulin stabilizes high BG level

The most common type of diabetes are Type-1 diabetes and Type-2 diabetes. Some women have Gestational diabetes during pregnancy. There are also some other types though most people suffer from type-1 and type-2 diabetes according to the researches. In type-1, human body stops producing insulin whereas in type-2 cells have insulin resistivity and cannot use insulin properly [1.3]. Thus, blood glucose level increases in both cases.

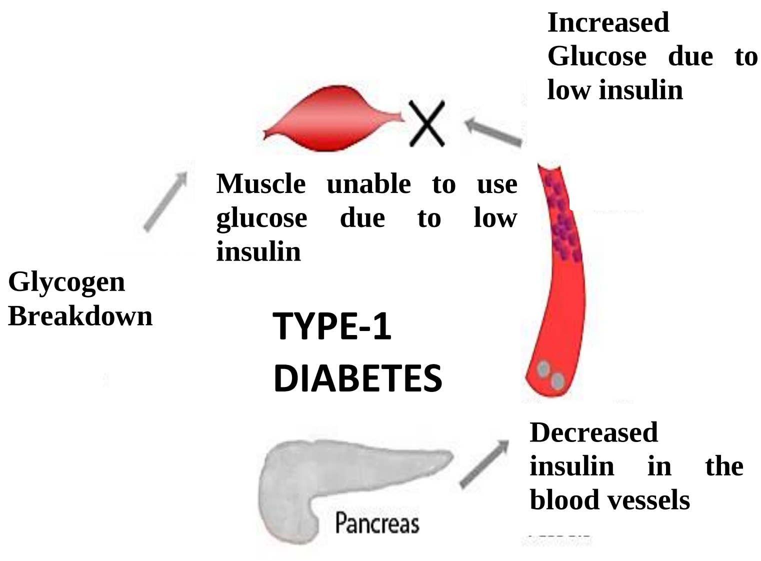


Figure 1-3. Type-1 Diabetes Problem

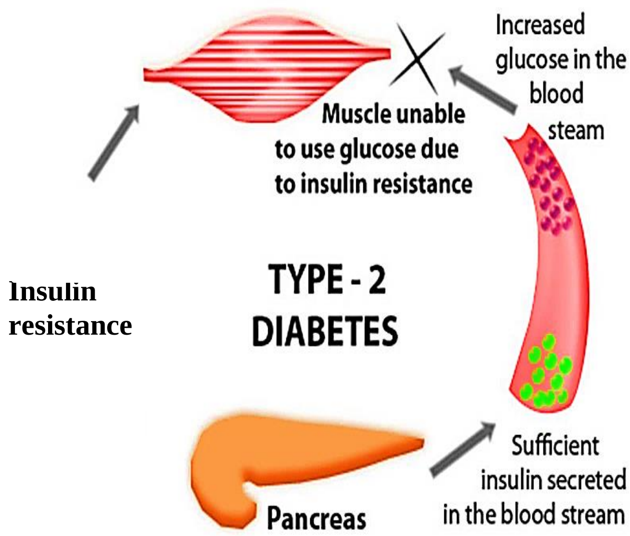


Figure 1-4. Type-2 diabetes problem

1.3 Symptoms

Depending on the sugar or glucose level in our blood diabetes is classified as- hyperglycemia and hypoglycemia. Hyperglycemia refers to high blood glucose (blood sugar). On the other hand, hypoglycemia is the term that describes very low blood glucose level. These two are sensitive cases in diabetes problem.

Several symptoms are observed on daily basis if a person has diabetes. Figure 1-1 shows different signs of diabetes.

Figure 1-5. Different Symptoms of diabetes

Figure 1-6. The Effects of diabetes on human body

1.4 Elements of Blood

Blood is a specialized body fluid. It is composed of four main components: plasma, red blood cells, white blood cells, and platelets. Blood transports oxygen and nutrients into the lungs and tissues to form blood clots and prevent excess blood loss. It also carries cells and antibodies which fight infection. Blood also brings waste products to the kidneys and liver, which filter and clean the blood by regulating body temperature. The blood flowing through the veins, arteries, and capillaries is known as whole blood. The whole blood is a mixture of about 55 % plasma and 45 % blood cells [1.4].

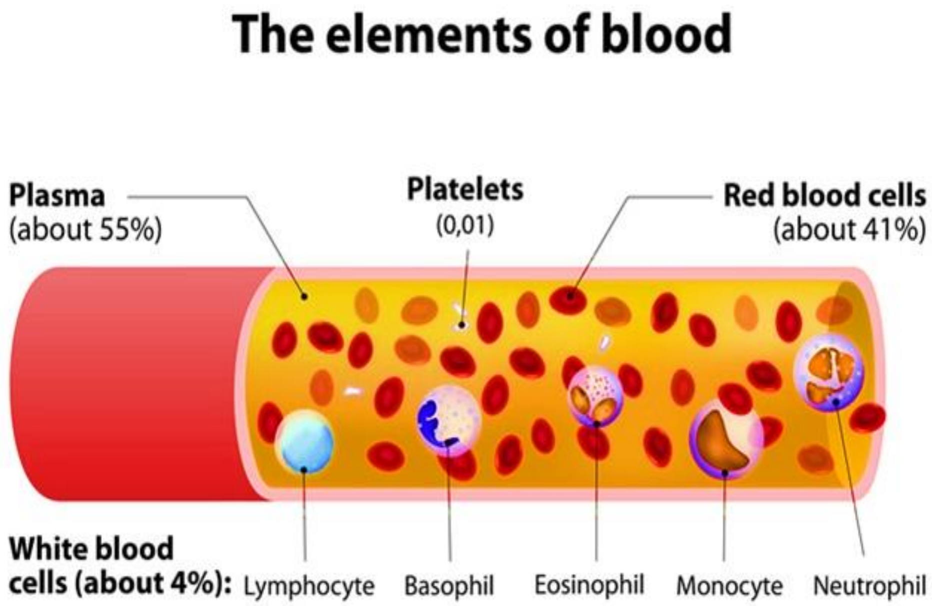


Figure 1-7. Components of Blood

1.4.1 Plasma, Blood cells and Glucose

The liquid component of blood is known as plasma. Plasma is a mixture of water, sugar, fat, protein, and salts. The main job of plasma is to transport blood cells throughout your body along with nutrients, waste products, antibodies, clotting proteins, chemical messengers such as hormones, and proteins that help maintaining the body's fluid balance.

HbA1c Test score	Mean Blood Glucose mg/dl	Glucose Mmol/L
14.0	380	21.1
13.0	350	19.3
12.0	325	17.4
11.0	280	15.6
10.0	250	13.7
09.0	215	11.9
08.0	180	10.0
07.0	150	8.2
06.0	115	6.3
05.0	80	4.7
04.0	50	2.6

Table 1-1. A reference chart for HbA1c, Mean Blood and Glucose in human body

Plasma contains sugar. Sugar in our body is known as glucose. When glucose builds up in our blood, it binds to the hemoglobin in our red blood cells. The A1c test measures the amount of bound glucose. The hemoglobin A1c test depicts the average blood sugar level over the past 2 to 3 months. It is also known as HbA1c, glycated hemoglobin test, and glyco hemoglobin. Red blood cells have a life span of about 3 months. Therefore, the test shows the average blood glucose level for the past 3 months.

In a healthy human body, the blood glucose level fluctuates from 70 mg/dl to 180 mg/dl normally in a day while fasting [1.5]. If the glucose level exceeds 230 mg/dl, diabetics might experience a hyperglycemia and hypoglycemia occurs if the BG level is less than 65 mg/dl [1.6].

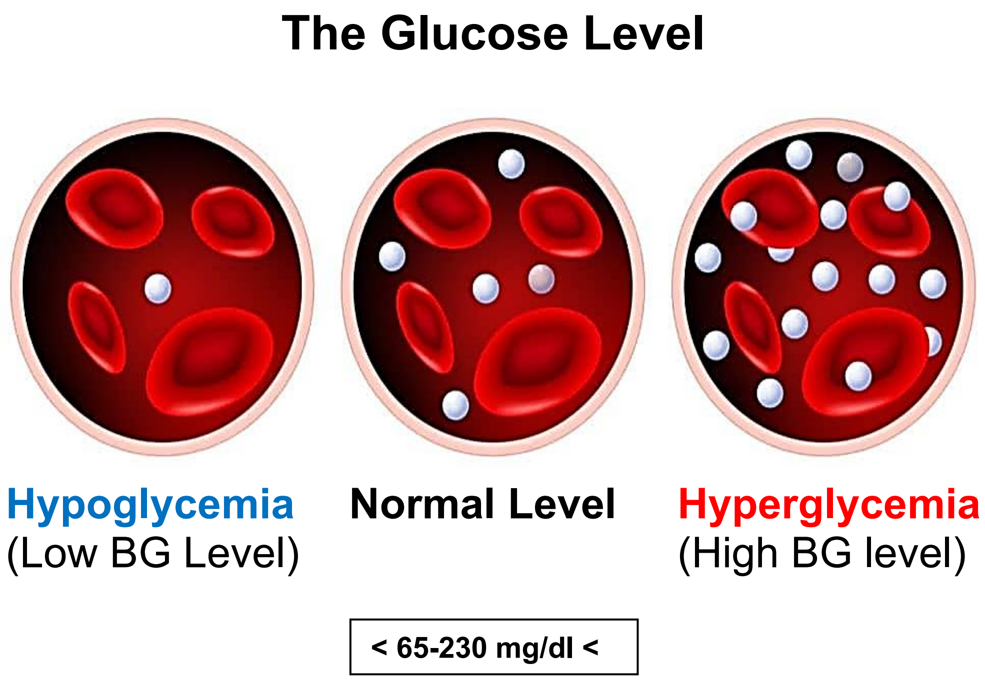


Figure 1-8. Glucose Level in human body

Diabetic patients need this test regularly to check if their blood glucose levels are staying within the range. Depending on the results patients need to adjust their diabetes medicines. There is no absolute cure for this disease though its control is possible. Therefore, monitoring of BG level is necessary.

Chapter 2

2.1 Methods of Monitoring BG Level

Generally, patients go to the hospital to check up their blood sugar level. Normally, for diagnosis plasma blood is collected from capillary during fasting. Then, after 2 hours another test is done with glucose uptake. Finally, the test result is given. This is the most reliable way to measure glucose level in blood. However, this takes a lot of time and is very costly. For a diabetes patient is important to monitor his BG level time to time to avoid any complications. Therefore, a GL monitoring device is a necessity which is portable, cost effective and hassle free. It helps to have precautions and take any measure immediately in case of serious health issue.

There are several methods to monitor blood glucose level. They can be classified as conventional and non-conventional methods.

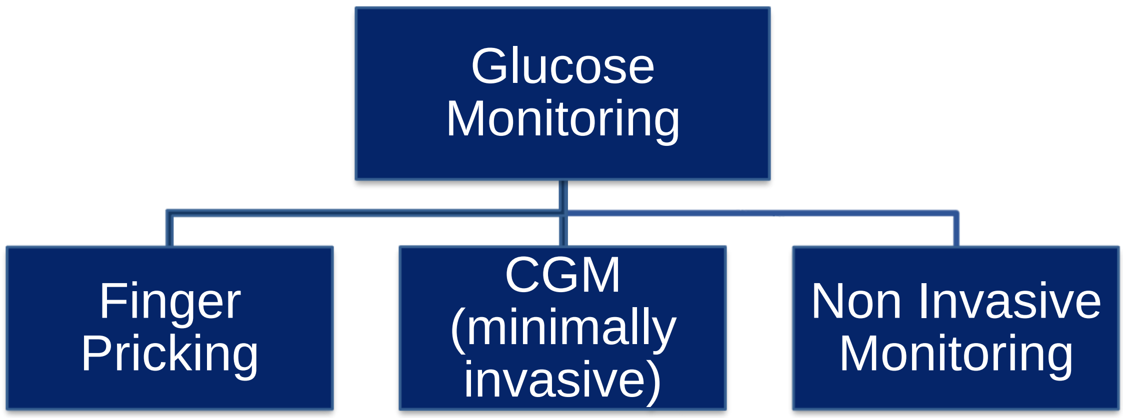


Figure 2-1. Glucose monitoring Methods

Finger pricking method measures glucose level from the collected blood sample. Continuous Glucose Monitoring (CGM) tracks glucose level throughout the day and night at regular intervals. Some CGM devices are implantable and some are minimally invasive. Non-invasive Monitoring refers to no penetration of the skin or surgery for sensor implantation.

2.1.1 Finger Pricking

The conventional method requires finger pricking or syringe injecting to collect blood from the patient, which is very painful, time consuming and very costly [2.1-2.4]. The toll becomes heavier when the patient needs to check it twice or more in a day regularly. Therefore, there has been a huge research effort for noninvasive, continuous glucose monitoring methods which can solve all these problems [2.5-2.8].

Figure 2-2. Painful Finger Pricking method

2.1.2 Continuous Blood Glucose Monitoring (CGM)

Today, continuous blood glucose monitoring (CGM) devices with different types are available. Some of the devices are implantable and some are minimally invasive. The most common ones are enzyme based (glucose-oxidase) devices which are mounted top on the skin and a needle is inserted into the body [2.9-2.10]. The needle goes to the thin layer of fluid level known as interstitial fluid (ISF) under the skin. Interstitial fluid (ISF) surrounds the body cells. From blood vessels, glucose and other components come to the ISF by diffusion and osmosis process.

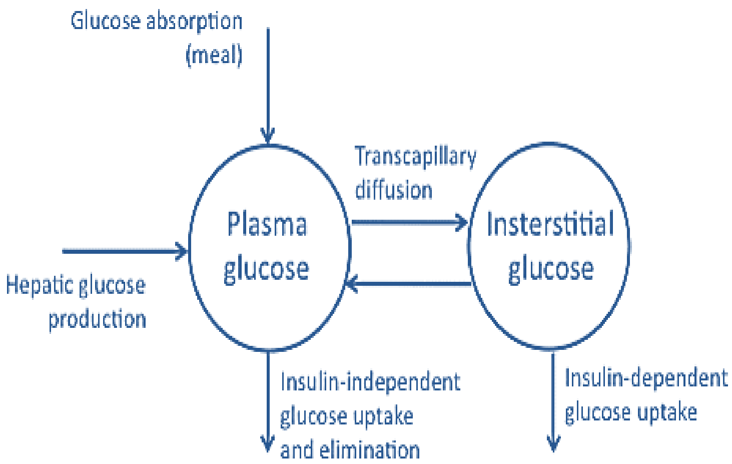


Figure 2-3. Sharing of glucose and other components between plasma and interstitial fluid through diffusion

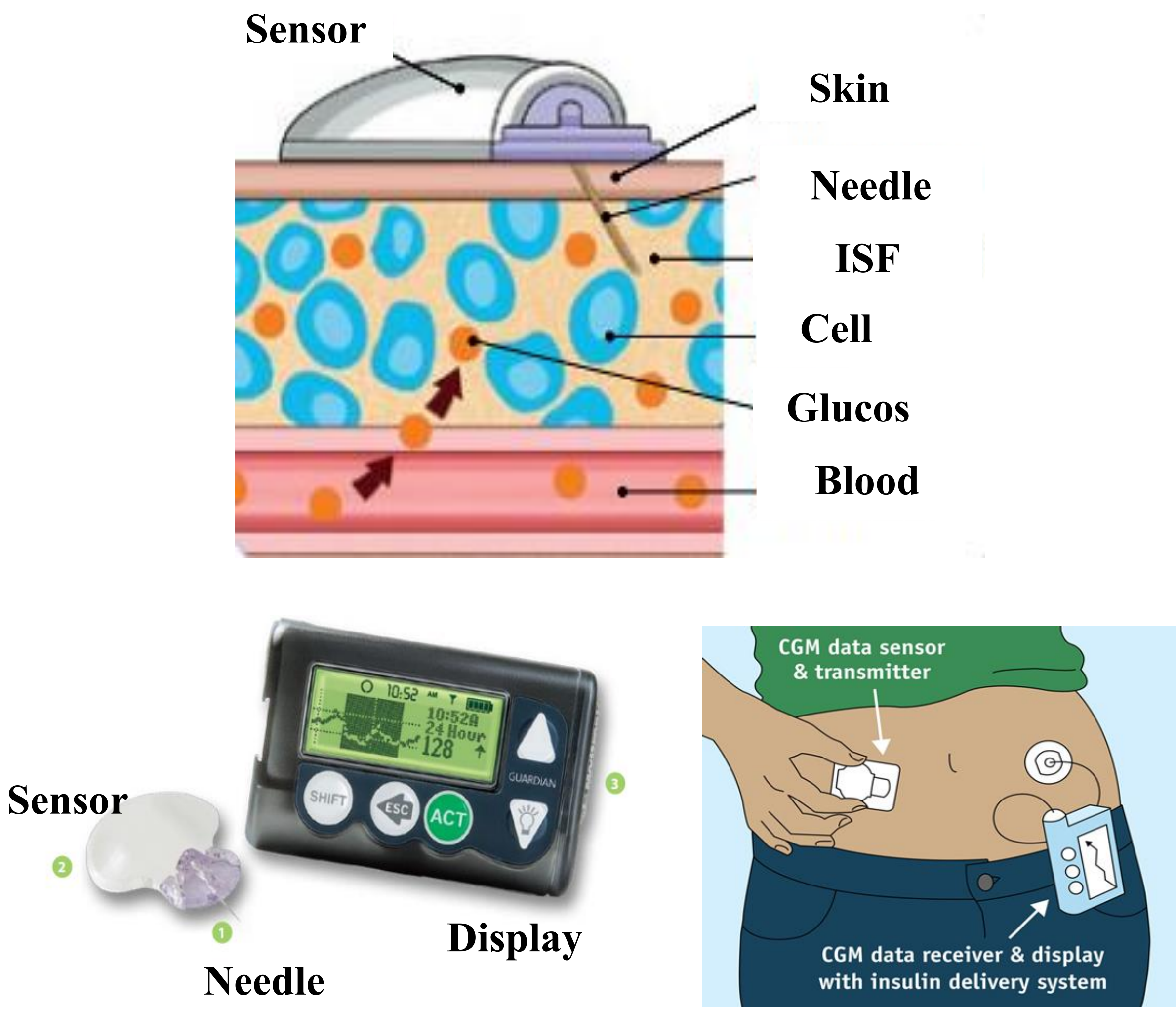


Figure 2-4. Continuous Glucose Monitoring Device and Working principle

Various researches show a good correlation between ISF and plasma blood glucose. ISF allows CGM devices to measure the glucose level. The sensor is an electro-enzymatic sensor. Needle tip contains the enzyme glucose oxidase. Enzyme reacts with only glucose and produce H_2O_2. From H_2O_2, O_2 and electron (e^-) is produced. Current is measured from the reaction which is directly proportional to the amount of glucose [2.9-2.10]. The result is shown on the monitor and insulin is pumped into the body of the patient accordingly.

2.2 Problems and Complexity

The major demerits of this minimally invasive, continuous, self-monitoring devices are discomfort and pain, rashes on the skin and expensiveness [2.11]. Many of the CGM devices have been reported less effective in daily life use and different physiological problems [2.12].

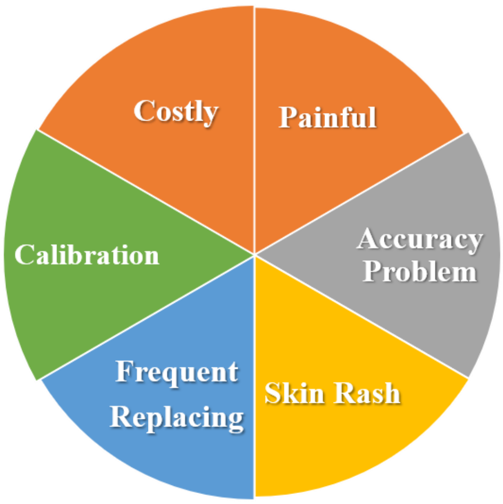


Figure 2-5. Demerits of the Continuous Glucose Monitoring Devices

Figure 2-6. Drawbacks of the CGM Devices

Apart from electrochemical sensors there are other noninvasive techniques which have been explored by the researchers. Several techniques like impedance spectroscopy, fluorescence technology, optical coherence tomography etc. are showing good accuracy, however, they suffer from calibration problems, size and complex circuitry arrangements.

2.3 Microwave Technique

Microwave technique has already found its applications in cancer detection and other bio-medical fields. Nowadays, is a new physical approach for NIBGM [2.13-2.17]. Microwaves can penetrate through the body by few centimeters and needs less power which makes it non-ionizing. Therefore, this method can provide continuous readings precisely, safer and faster [2.18].

2.3.1 Why Microwave Ring Resonator

A microwave ring resonator features the noninvasive measurement of glucose level in a nondestructive fashion. They have specific resonant characteristics i.e. resonance frequency, bandwidth and quality factor, depending on their physical dimensions and the dielectric properties of the substrate [2.19]. Many researchers find ring resonators attractive and suitable for glucose level sensing because they use low power with flexibility of design and fabrication process which is simple as well as cost effective.

Chapter 3

3.1 Microwave Ring resonator

The microwave ring resonator is a simple circuit which supports only waves that have an integral multiple of the guided wavelength equal to the mean circumference. With little modification many more complicated circuits can be created. For example, by cutting a slit, adding a notch, cascading two or more rings, implementing some solid-state devices, integrating with multiple input and output lines, and so on.

For the 1st time in the history, to measure the phase velocity and dispersive characteristics of a microstrip line, microstrip ring resonator was proposed by O. Troughton in 1969. The applications were only concentrated on measurement of discontinuities of a microstrip lines. However, by 1980, various applications of ring resonator, such as filters, oscillators, mixers, couplers, antennas and frequency selective surfaces emerged. At present days Microwave ring resonators are being studied for bio sensing for simple, low cost, compact and label free sensing [3.1]. The resonant characteristics of this kind of electromagnetic resonators can be easily controlled by modifying their geometrical structure and the physical properties of the experimental environment [3.2].

A ring resonator is essentially a transmission line formed in a closed loop which consists of the feed lines, coupling gaps and the resonator. The function of feed lines and coupling gaps are to couple the power into and out of the resonator.

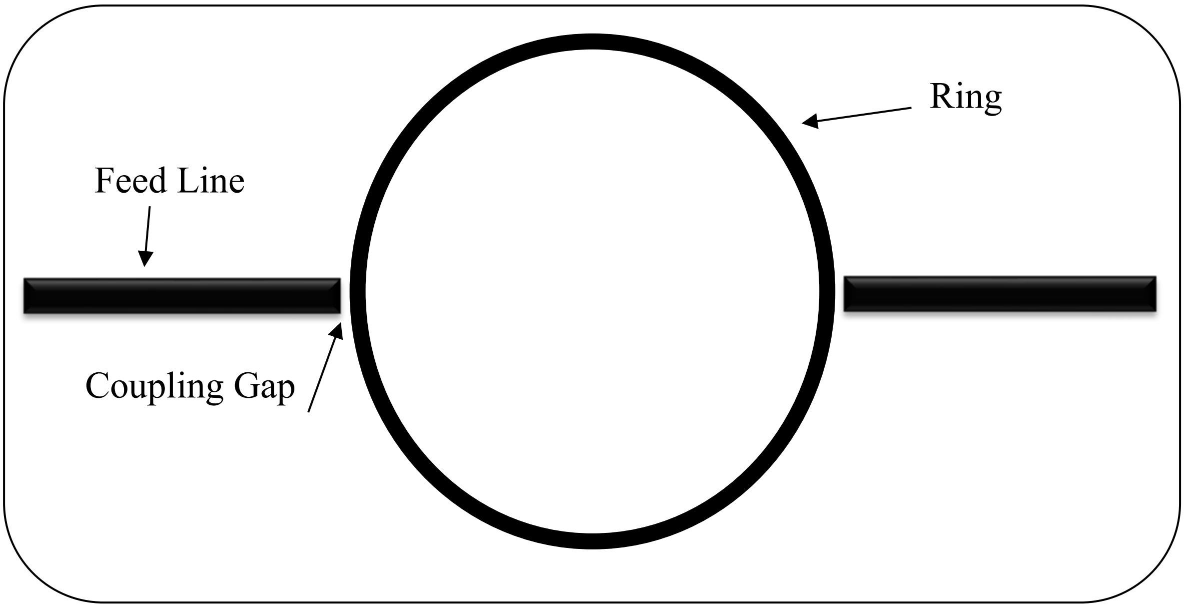


Figure 3-1. Annular Ring Resonator

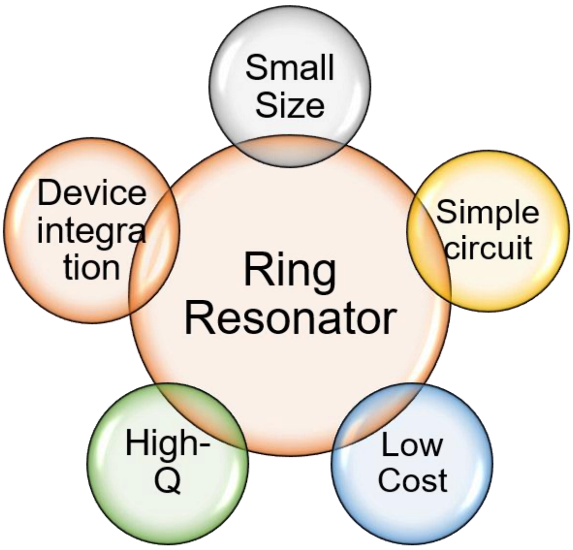
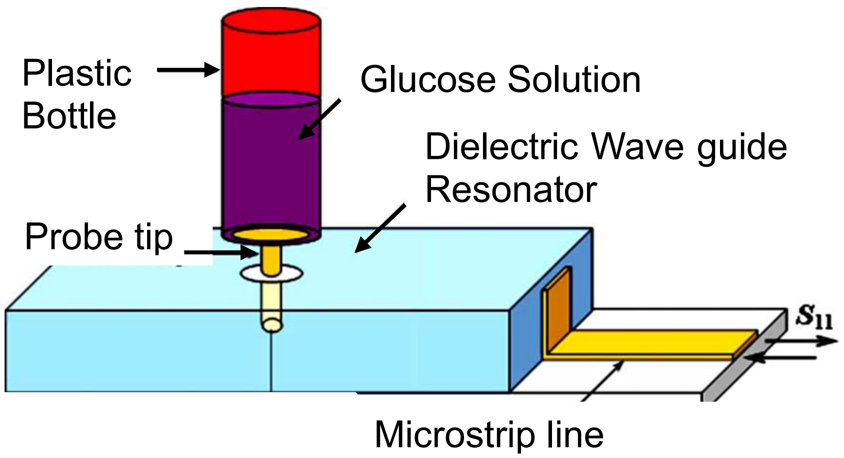


Figure 3-2. Advantages of Ring Resonator

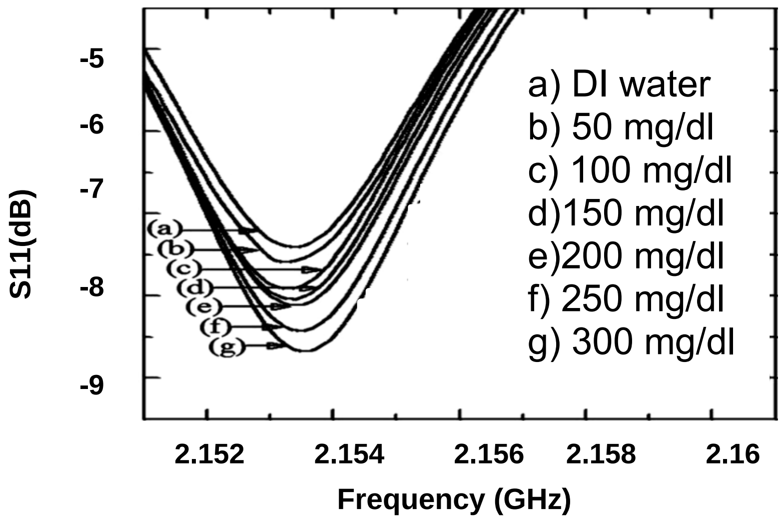
3.2 Preliminary Research

Different researchers have reported different and unique approaches to conduct their researches on ring resonator as GL sensor. The sensing methods are based on modification of geometry and shifts in the resonance peak, frequency or phase in the presence of sample aqueous glucose solution.

A paper by Dr. Ki jin Lee et.al showed microwave dielectric probe sensor for aqueous glucose sensing. Aqueous glucose solution was varied from 0-300 mg/dl, within the frequency range of 2-2.5 GHz. This paper also showed the relation between permittivity and concentration. With the increase in glucose concentration, permittivity also increases and the S parameter value decreases.



(a)

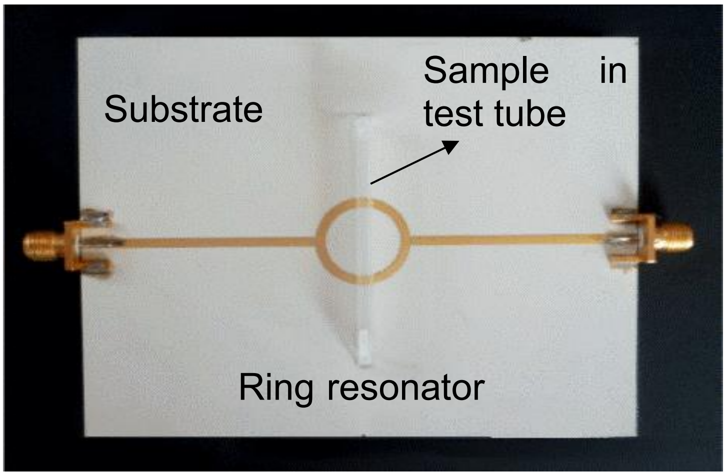


(b)

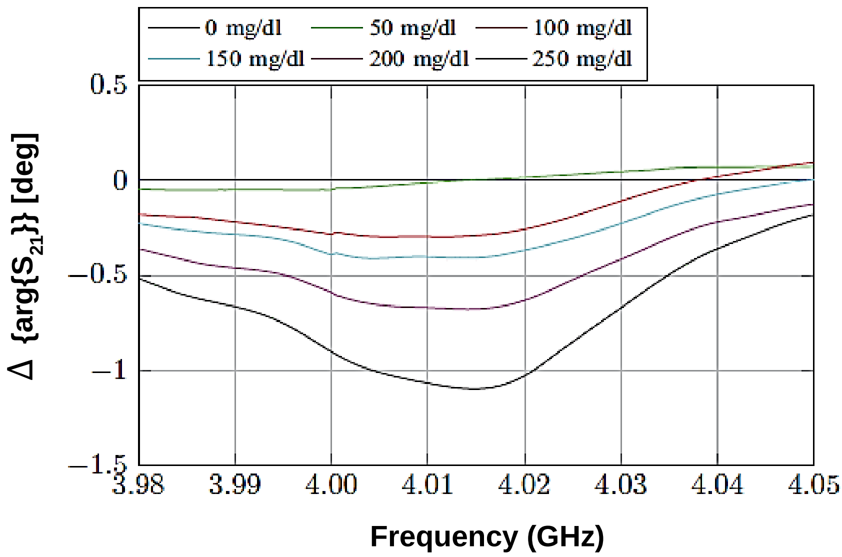
Figure 3-3. (a) Bulk Microwave probe Technique (b) S11 vs Frequency graph: Concentration changes permittivity and hence the frequency

Although this research shows important information for the microwave sensing, it has some drawbacks. This type of bulk sensor has low sensitivity, and high dielectric loss of the substrate. The literatures [3-3] and [3-4] also agree on this correlation between permittivity and concentration change.

In [3-5] authors used ring resonator as a glucose sensor. In this research glucose level sensing has been showed by means of phase shift of S21 parameter.



(a)

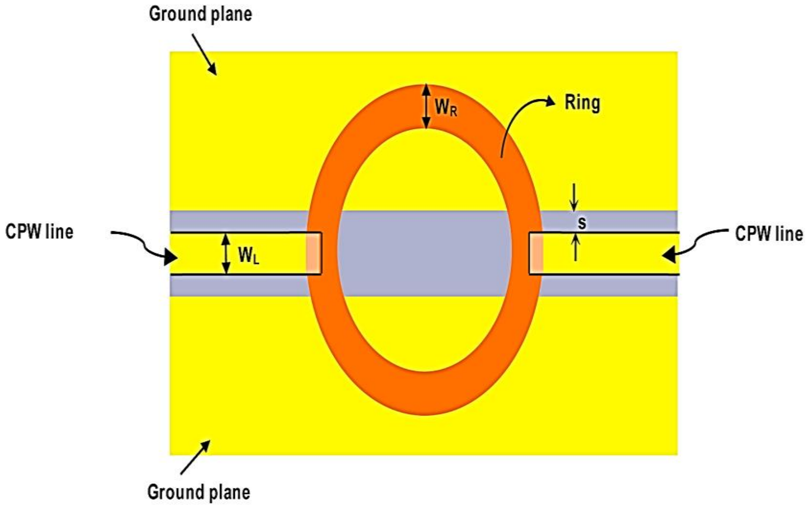


(b)

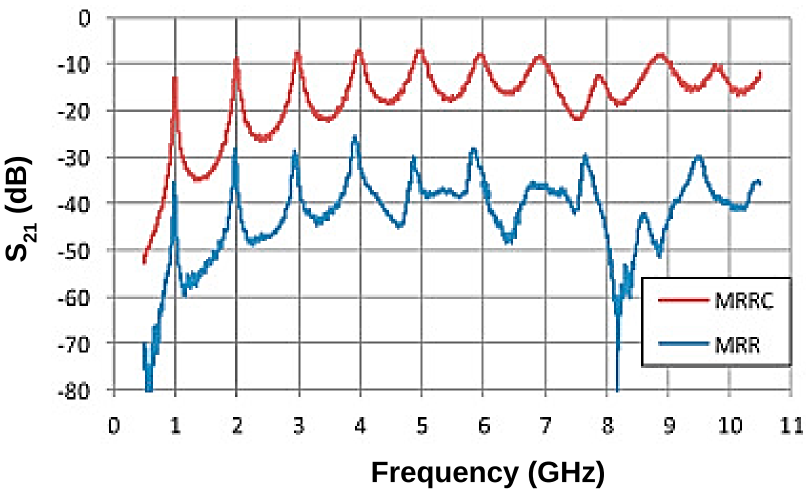
Figure 3-4. (a) Microstrip Ring Resonator **(b)** Phase shift property analysis

However, it has sensitivity problem as power is less coupled through this kind of structure.

In [3-6] Authors show an improved microwave ring resonator model with coplanar waveguide feed technique. Reported experiments for external glucose sensing from some animal tissue. Though it shows an improved ring resonator structure, but this type shows high harmonics problem. To suppress these harmonics no measures reported. Harmonics increases the BW which is not desirable in specific application.



(a)



(b)

Figure 3-5. (a) Microstrip Ring Resonator Co-planar wave feeding, **(b)** A Performance comparison of MRR and MRRC

3.3 Findings, Drawbacks and Challenges

The literature survey provided ample idea to approach for our research. One important finding from the survey is, the sample should be placed on the surface of the resonator, in a region where the electric field is highly concentrated to achieve most interaction between the glucose sample and operating frequency. high dielectric constant interacts with the EM field of the ring resonator and utilizing this property the S parameter analysis is conducted.

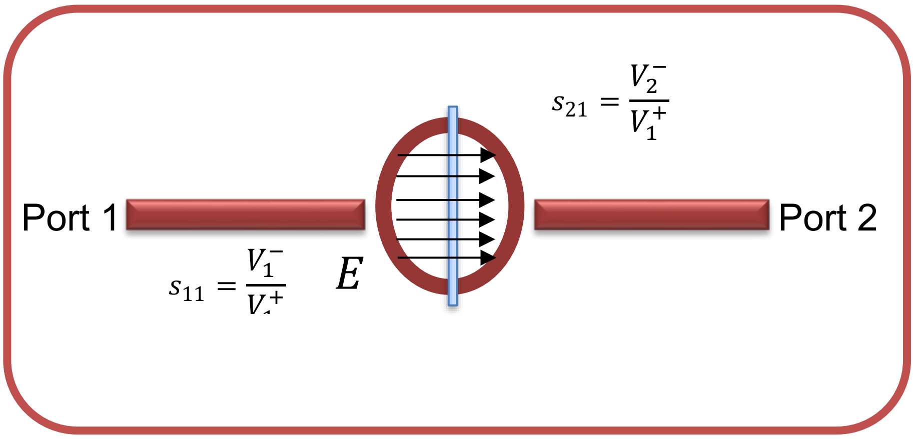


Figure 3-6. Microstrip Ring Resonator EM field interacting with the sample

Study of the researches underlined some common problems which should be considered as key factors for future researches. The dielectric loss of the substrate and low coupling strength cause the low power and major losses. If less power is coupled and the size of the substrate is not appropriate according to the application, the insertion loss becomes high and eventually BW and quality factor also degrades. As a result, the sensor cannot have a good sensitivity. All these problems have been found in preliminary researches. After studying these preliminary researches, it appears explicitly that the challenge lies in sensing the glucose concentration level in low concentration range. Moreover, the effect of the temperature and volume should be considered.

Chapter 4

4.1 Goal and Approach

The main goal is to design an external non-invasive glucose sensor based on microstrip ring resonator which will have improved Sensitivity. For the design of the proposed model we also consider the draw backs found in preliminary researches. Feasibility of the microstrip ring resonator sensor is analysed by sensing the aqueous glucose solution. Results are reported by observing the frequency shift in transmission coefficient S_{21}.

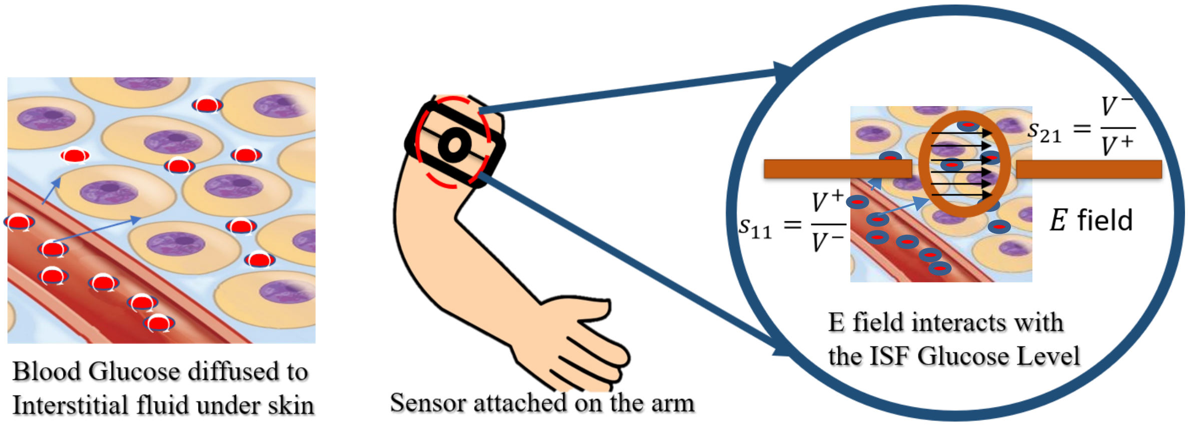


Figure 4-1. Conceptual Presentation of the Proposed sensor

The external non-invasive MRR based sensor will be attached to the arm. The EM fields interact with the interstitial fluid glucose level. The property change of the ISF glucose level will be recorded and shown as the measurement result. Mapping the frequency shift trend due to glucose level changing will help to have a better analysis of the scenario.

It is important to understand the features of the ring resonator and consider the microstrip feed line circuitry before designing the proposed sensor. Geometrical effects are also considered while designing as these parameter changes the behaviour of the resonator.

4.2 Coupling Gap Effect

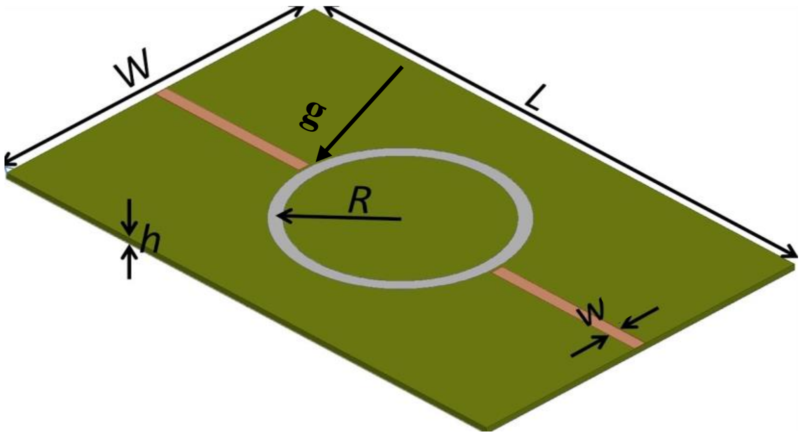


Figure 4-2. Basic Ring Resonator Design

Firstly, we designed the basic ring resonator. It is the first step to design a complex microstrip ring resonator circuit. Figure (4-1) shows different parameters of the ring resonator.

W = Width of the Substrate

w= Width of the microstrip line

h= Thickness of the substrate

R= Ring mean radius

g= Coupling gap

To operate the sensor in 1GHz we chose FR4 substrate. The control parameter of a ring resonator is the radius.

$$\boldsymbol{f_n = \frac{nc}{2\pi R\sqrt{\varepsilon_{eff}}}} \tag{1}$$

r=radius of the ring ε_{eff}=Effective dielectric constant

c=Speed of Light f_n= Solution Frequency n= 1,2,3…….

$$\boldsymbol{\varepsilon_{eff} = 3.22} \text{ (For FR}_4\text{)} \tag{2}$$

ε_e =Static Value of the effective dielectric constant

$\varepsilon_r =$ Relative dielectric Constant

$$\boldsymbol{\varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\left(1+\frac{12h}{w}\right)^{-0.5} + 0.04\left(1-\frac{w}{h}\right)^2\right] \qquad \text{if } \frac{w}{h} \leq 1}$$

$$\boldsymbol{\varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\left(1+\frac{12h}{w}\right)^{-0.5}\right] \qquad \text{if } \frac{w}{h} \geq 1}$$

We assume the coupling gap is g, where-

$$\mathbf{g} = \mathbf{0.421d}\left(\frac{\varepsilon_{eff}+0.3}{\varepsilon_{eff}-0.258}\right)\left(\frac{\varepsilon_{eff}+0.262}{\varepsilon_{eff}+0.818}\right) \quad (3)$$

The Basic model of the ring resonator is also known as loose coupled resonator.

4.2.1 Loose Coupling

The coupling gap is a distance that keeps the feed lines separated from the resonator. Power is coupled into and out of the resonator through feed lines and coupling gaps. There are different types of coupling. Most common one is loose coupling. This method is widely used for the design of the ring resonators. Depending on the distance between the feed lines and the resonator, coupling gaps can affect the resonant frequency. If the distance is large or the coupling area is small, then it is termed as “loose coupling” which is a manifestation of negligibly small capacitance if the coupling gap. A large gap and small coupling area yield less field perturbation though greater losses are compromised. Fig 4-3 shows E field analysis in simulation model of the loose coupled ring resonator.

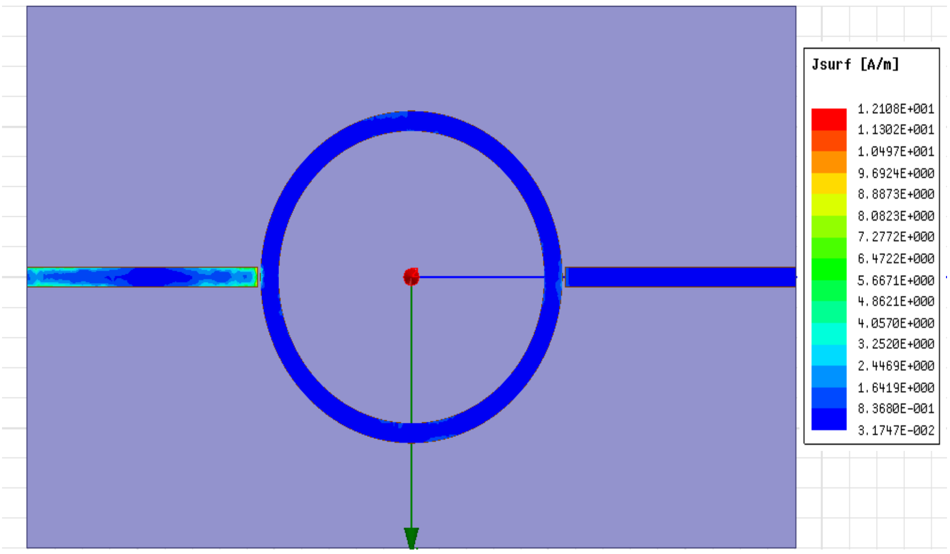


Figure 4-3. Simulation result: Surface current analysis for loose coupling

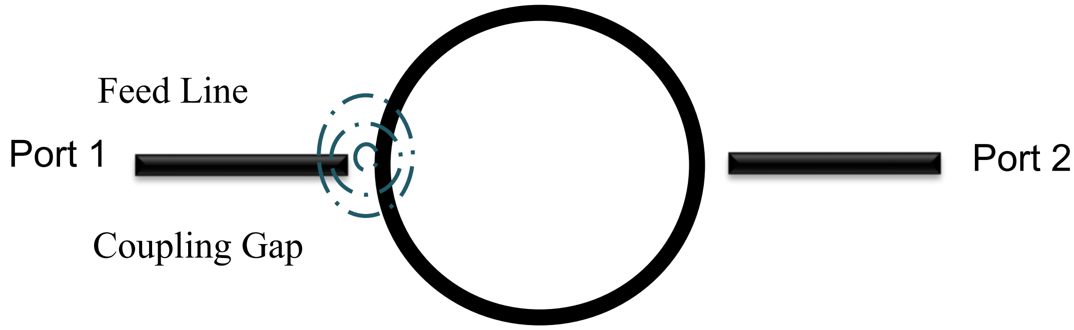


Figure 4-4. Coupling Gap Effect

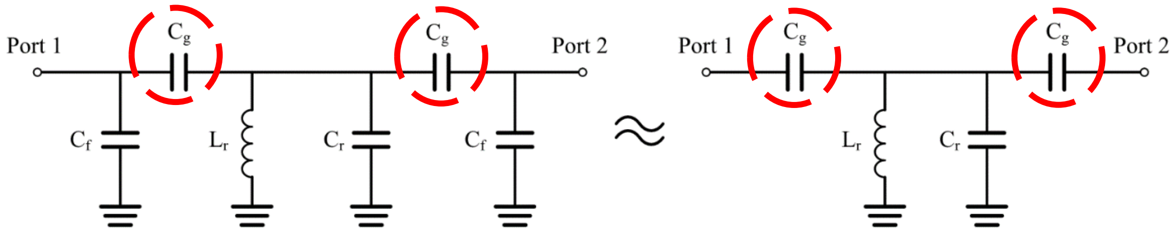


Figure 4-5. Equivalent circuit for Feedline and Coupling gap for two port ring

To make the ring resonator work as a glucose sensor, we must need more power to be drawn from the feed line. Therefore, the coupling problem must be solved in priority basis. The microstrip ring resonator can be expressed by equivalent circuit models. The equivalent circuit of a ring resonator with coupling gap is explained briefly. Figure 4-5 is the equivalent circuit model for the single port ring resonator. The parameters are as follows-

C_g = Coupling Gap Capacitance

C_f = Feed line capacitance

C_r = Capacitance of the Ring

L_r = Inductance of the Ring

$$L_r = \frac{1}{{\omega_0}^2 C_r} \qquad C_r = \frac{\pi}{Z_0 \omega_0} \qquad C_g = \frac{\varepsilon_0 \omega_0 t}{g}$$

$$\text{Angular Frequency, } \omega_0 = \frac{1}{\sqrt{L_r (C_r + C_g)}}$$

With the change of the coupling gap distance the total coupling area changes and parameters are varied. We want to improve the coupling capacitance. When the feed line is closer to the resonator, it improves the coupling and increases the capacitance. Increasing the total coupling area will also increase the C_g. Therefore, capacitance due to coupling gaps is considered as a vital parameter to design a ring resonator based sensor.

4.2.2 Enhanced Coupling Periphery

Loose coupling method is very popular with high -Q resonators. However, unfortunately this method suffers from high insertion loss due to having a small coupling area. Therefore, it is required to improve and increase the coupling strength (Cg) between feed lines and the ring resonator. If the coupling area is increased the coupling becomes tight. In this type of coupling, coupling periphery is increased by punching the feed line into the annular ring element.

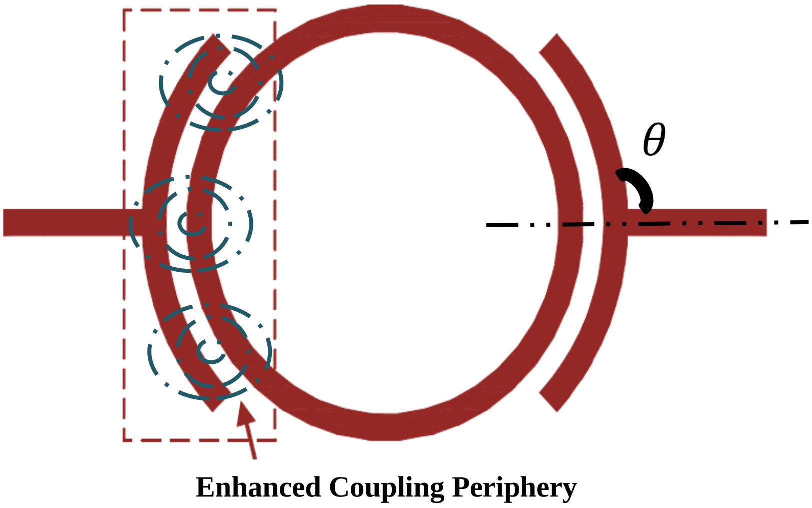


Figure 4-6. Enhanced Coupling

At f= 0° and f = 180°, where the field is maximum, if some discontinuities are present, the fields of the ring are least perturbed. The increase in the coupling periphery at these points will reduce the insertion loss of the ring with negligible field perturbation. Figure 4-6 shows the increased coupling periphery. There is a microstrip line bending due to the arc shape. The microstrip line has a typical bend for an arbitrary angle θ with the reference plane. Maintaining the ratio of the chamfered region width and microstrip line width resulted in optimum design of the chamfer.

Due to the bend in the microstrip line the equivalent circuit can be modeled as shown in figure 4-5, an equivalent circuit can be modeled.

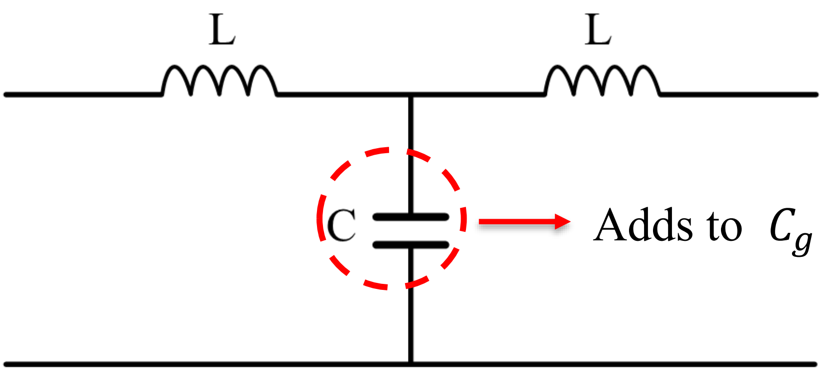


Figure 4-7. Equivalent circuit due to microstrip bending

We can improve the coupling by enhancing the coupling area or periphery. As the coupling area increased more power is drawn from the strip line. Due to micro strip bending there comes an equivalent capacitance which is added parallelly to the Cg. Thus, two parallel capacitances increase the coupling capacitance.

$$C = 0.001h\left(\frac{180-\theta}{90}\right)[(3.393\varepsilon_r + 0.62)(\frac{w}{h})^2 + (7.6\varepsilon_r + 3.8\left(\frac{w}{h}\right)]$$

$$L = 0.44h(\frac{180-\theta}{90})\ [1\text{-}1.062e^{-0.177(w/h)^{0.947}}]$$

4.2.3 Design of the proposed Ring resonator

Though we have improved Cg, we still need to improve sensitivity and need a strong E field zone for localization of the sample to be tested. In enhanced coupling E field arrangements is not strong inside the ring. Charges are distributed on the periphery only.

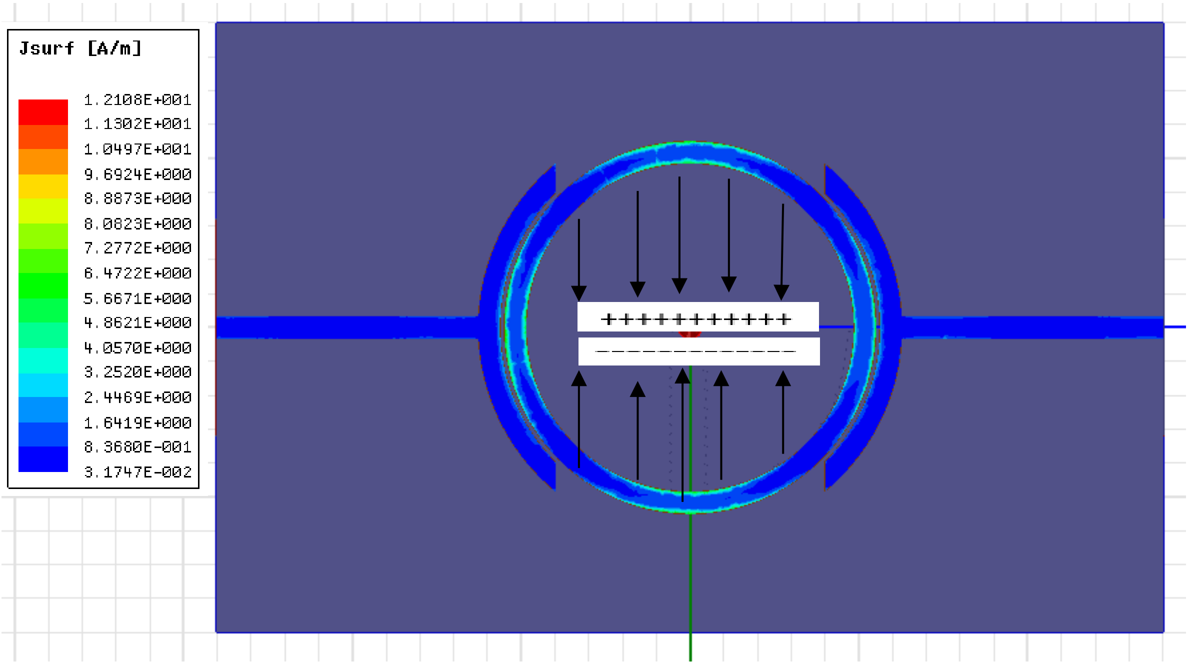


Figure 4-8. Simulation for surface current analysis of the Enhanced Coupling. Arrows indicate that if the charges on the periphery can be dragged inside the ring the coupling, sensitivity and Q factor will improve

If we can draw the charges from the periphery to the centre of the ring, the strong e field will be created. We are collecting the charges inside the ring from the 90° position or vertically. Not taking from 180° or horizontally because coupling will be disrupted

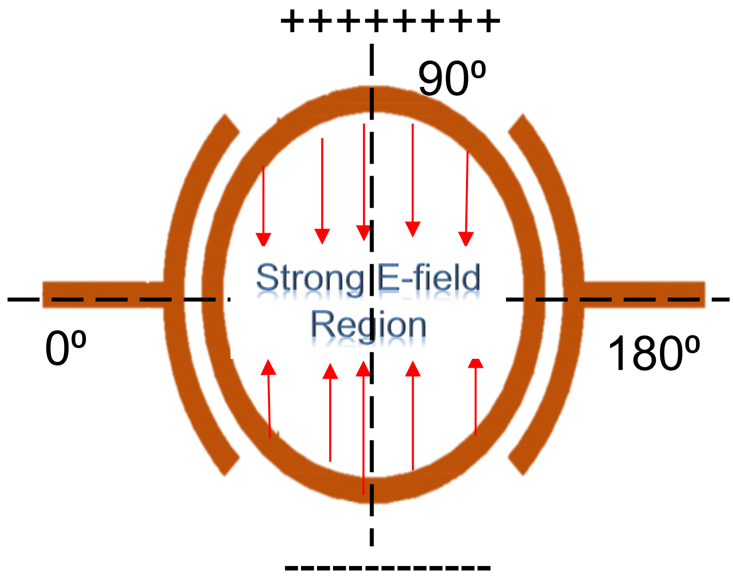


Figure 4-9. Charges on the vertical periphery concentrated to form strong E field region

4.2.3.1 Proposed Equivalent Circuit Model

The charges in the middle of the ring form a capacitance. It is in parallel with C_g and C_r.

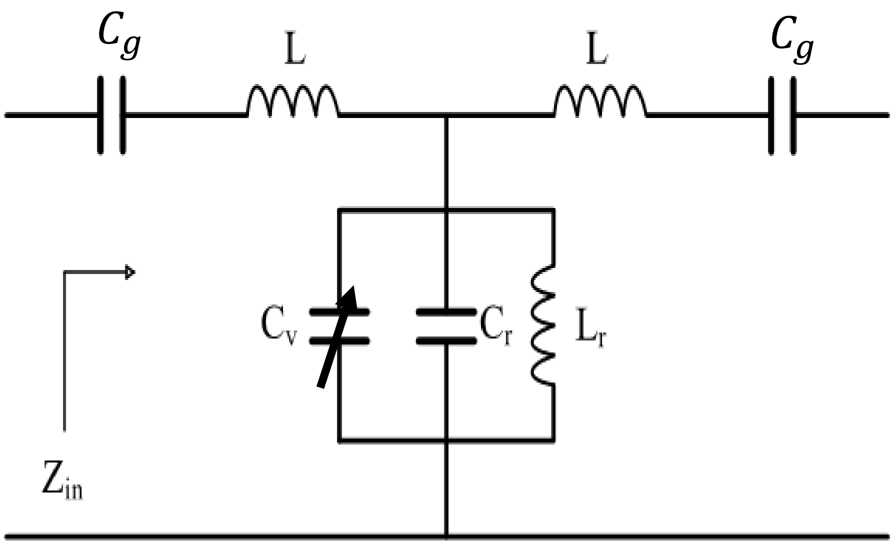


Figure 4-10. Equivalent Circuit of the Proposed Ring Resonator

The operating principle can be explained based on transmission line model and previously explained coupling gap effect.

The coupling gap and between the feedline and the ring is represented by a L network capacitance C_g and inductance L is due to the bended microstrip line. The feedline and the arc compose the enhanced coupling mode which increases the coupling strength between feed lines and ring resonators. The ring resonator is expressed by L_r and C_r. A variable capacitance C_v increases the capacitance inside the ring which will also have the effect of C_g and microstrip bending. The total input impedance of the simple equivalent circuit would be-

$$\boldsymbol{Z_{in}} = \frac{j[\omega^2 L_r(C_r+C_g+C_v)-1]}{\omega C_g(1-\omega^2 L_r(C_r+C_v)} \tag{4}$$

where, ω= angular frequency. At resonance, $Z_{in} = 0$ and the resonant angular frequency –

$$\boldsymbol{\omega_0} = \frac{1}{\sqrt{L_r(C_r+C_g+C_v)}} \tag{5}$$

Transmission Co-efficient $S_{21}$of the simplified equivalent circuit at ω_0 can be interpreted as-

$$\boldsymbol{S_{21}} = \frac{2}{2(1+Z_gY)+Z_g(2+Z_gY)/Z_0+YZ_0} \tag{6}$$

Where $\boldsymbol{Z_g} = \frac{L}{j\omega_0 C_g}$ and $\boldsymbol{Y} = \frac{j[(\omega_0{}^2 L_r(C_r+C_v))-1]}{\omega_0 L_r}$ and $\boldsymbol{Z_0}$= Characteristic Impedance=**50 ohm**.

Table (4-1) depicts the comparison of the capacitances of the loosely coupled model and the proposed model.

Parameter	**Value**
C_g (Loose Coupled)	60nf
C_g (The Proposed model)	105uf

Table 4-1. Comparison of the capacitances

4.2.3.2 Proposed Design

The proposed ring resonator is designed on a FR4 substrate which has a relative permittivity of 4.4 and dielectric loss tangent 0.02. A copper plated feed line is coupled with the ring. A variable capacitance introduced to strengthen the electromagnetic field inside the ring. The coupling between the microstrip line and the ring is an enhanced mode coupling which ensures increased coupling periphery and low insertion loss. The microstrip line has a typical bend for an arbitrary angle θ with the reference plane defining the edges of the bend. Maintaining the ratio of the chamfered region width and microstrip line width resulted in optimum design of the chamfer.

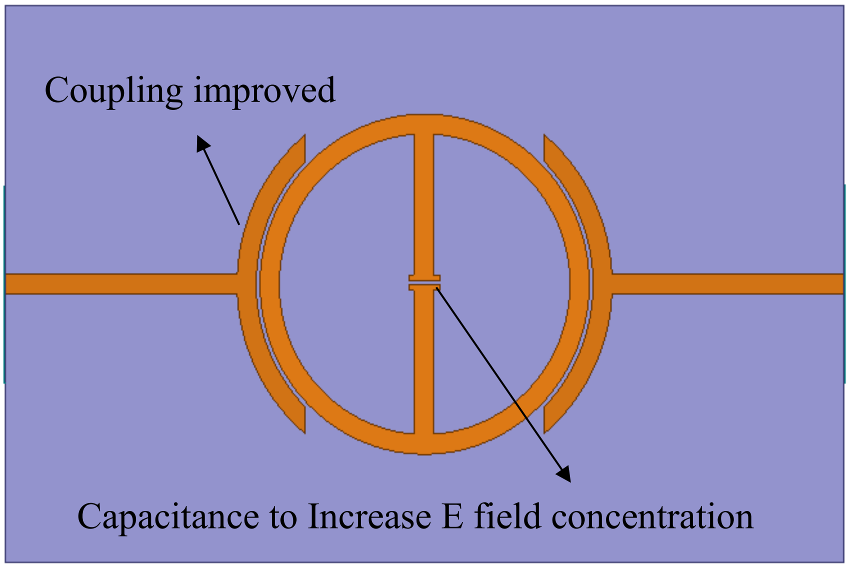


Figure 4-11. Proposed Ring Resonator

This is our proposed model. In the middle we have introduced the capacitance which makes strong e field, we can also see it from e field analysis. We have improved coupling, power issue and the arc supresses the harmonics hence BW is narrow meaning Q factor will be high, meaning sensitivity will improve.

Parameter	Symbol	Measurement (mm)
Substrate height/thickness	h	1.6
Feed line Width	w	3.2
Feed gap	g	0.64
Ring mean radius	R	26
Copper thickness	t	0.035

Table 4-2. Optimized parameters for proposed Ring Resonator

4.3 Simulation

E field analysis and surface current analysis were checked to find out the most concentrated electric field region of the proposed sensor. Expectedly, inside the ring, the capacitive zone shows the strongest E field profile in the analysis. Afterwards, we used this region for placing the sample on the sensor.

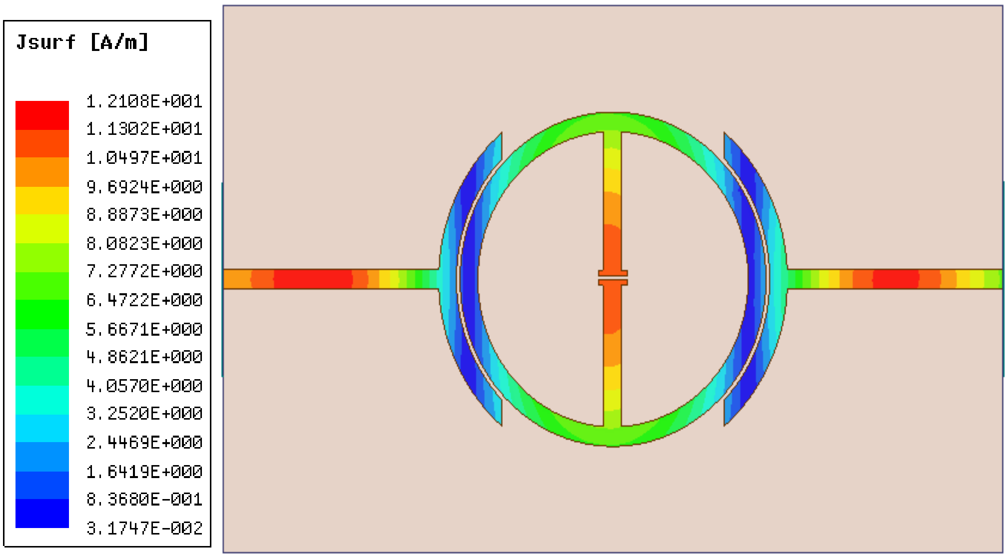


Figure 4-12. Surface current analysis predicts the strongest E field zone on the RR surface where the sample could be placed

At first, we check the resonant frequency for no load conditions. As the dielectric change is very low with the change in aqueous glucose concentration level, the number of points of simulation was increased to observe the S21 performance rigorously. In simulation two resonance frequencies are found. Mode-1 frequency zone is at 0.99 GHz while the mode-2 is at 1.37GHz. It was found that both mode-1 and mode-2 frequencies showed good sensitivity to the change in glucose concentration level. However, we are interested in mode 2 frequency region as mode 1 is due to the basic ring resonator and mode 2 is due to our proposed design. We also checked reflection coefficient S11 parameter to make sure the data is reliable.

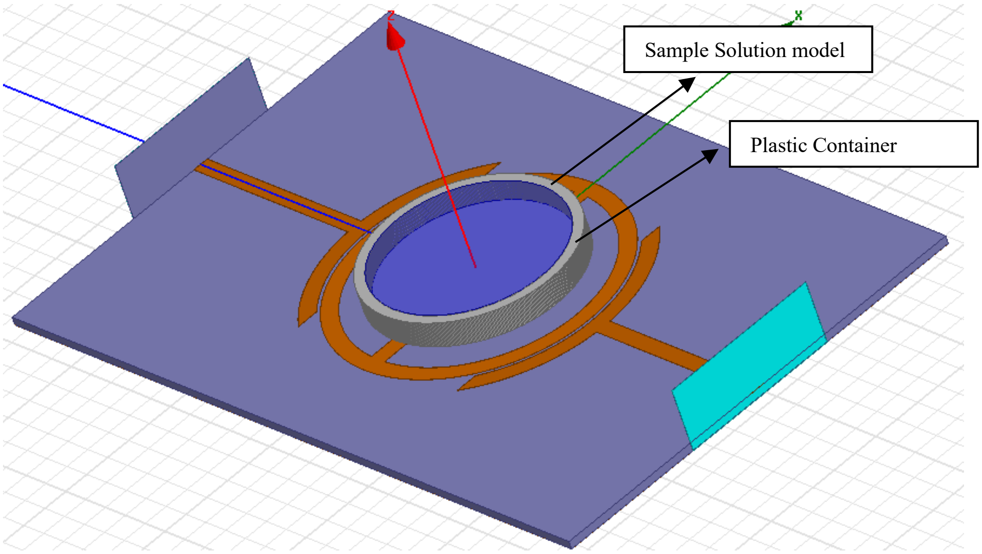


Figure 4-13. Simulation of the sensor in loaded condition

After evaluating the resonant frequency for no load condition, design of various load conditions and observation of the transmission co-efficient S21 performance were done.

Plastic container was designed to hold the sample on the surface of the resonator. In ANSYS HFSS. It is easy to define the samples individually by defining their material and other properties. We calculated the permittivity of different concentration level of aqueous glucose solution for our simulation. Relative permittivity depends on aqueous glucose concentration and is often expressed as the molar increment δ [4.1]. The relative permittivity of aqueous glucose solution can thus be expressed as

$$\varepsilon_g = (\varepsilon'_w + c\delta' - j(\varepsilon''_w + c\delta''))$$

$\varepsilon'_w =$ 77:388and ε''_w =8.242 for 2.15 GHz at 25℃ [4.2]

Sample is placed on the strong E field region of the sensor. Aqueous Glucose concentration has a very high dielectric constant. As the sample is placed on the surface of the ring resonator where the electric field is highly concentrated, the dielectric constant of the glucose concentration interacts with the EM field of the ring resonator.

From the figure 4-14 we can notice that the proposed ring resonator has 3MHz – 10 MHz shift in resonant frequency from both modes with the change in sample permittivity and concentration. This is an ideal condition for the experiments. It is expected that the experimental results can be different from the simulation results due to the practical environments.

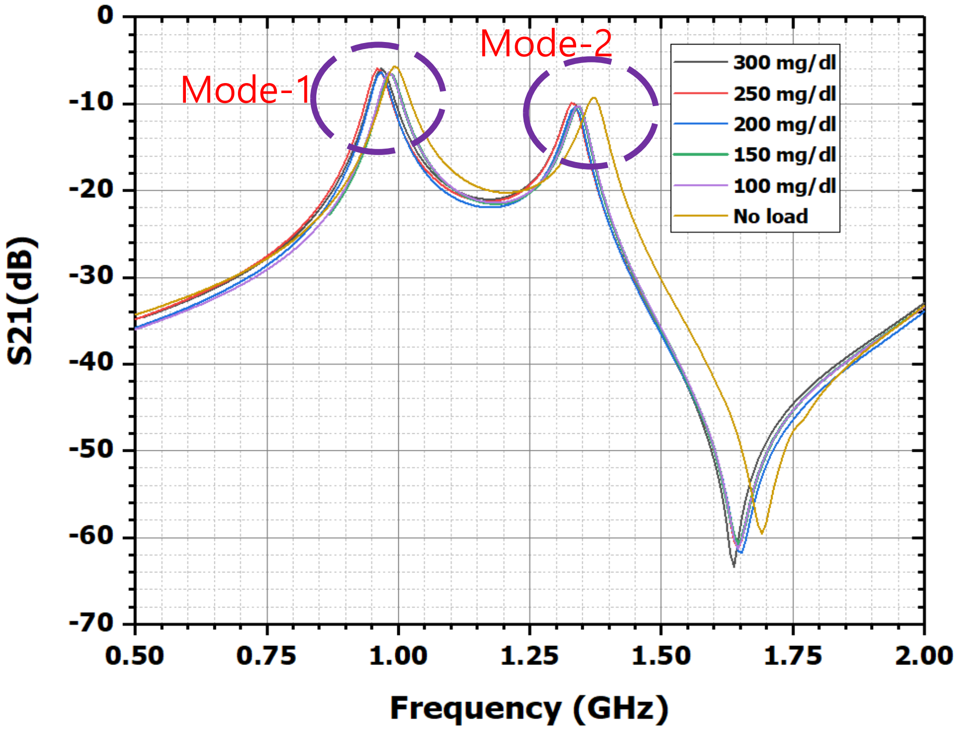


Figure 4-14. Simulation result (S21) for different concentration level of aqueous glucose solution

We calculated the quality factor from the simulation results with the given equation-

$$Q = \frac{f}{BW_{3dB}}$$

It was found that in no load conditions the quality factor differs negligibly. As mode 1 is for the basic ring resonator and mode 2 for the proposed sensor, we can calculate the BW and Q easily and compare them.

Parameter	Value
Q (Loose Coupled)	24
Q (Proposed Model)	40

Table 4-3. Comparison the q factors of the basic ring resonator and proposed design

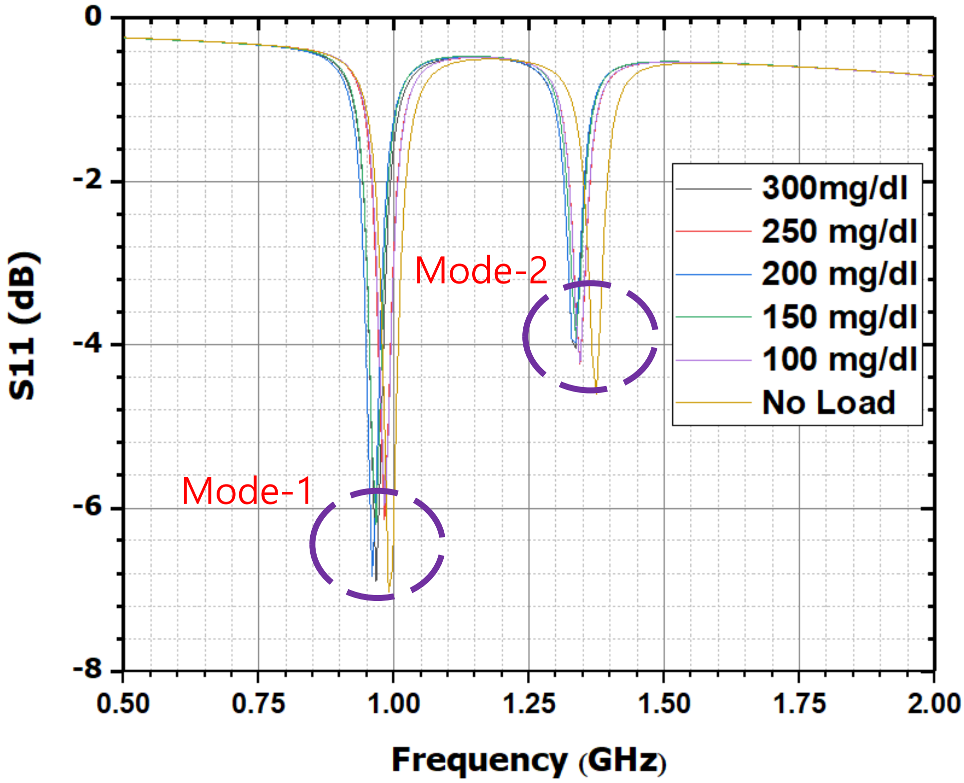


Figure 4-15. Simulation result (S11) for different concentration level of aqueous glucose solution

The S11 parameter shows that for the basic ring resonator at mode 1 frequency reflection loss is as high as -7dB. However, due to our proposed design, the S11 reduced to -4.5 dB at no load condition and -4dB at load conditions which is a great improvement over the basic model of the ring resonator. This is a proof that, the device can draw more power and low insertion loss is possible in this proposed sensor.

Chapter 5

5.1 Solution Preparation

For the experiment at first aqueous glucose solution was made. To make glucose solutions of different concentration levels DI water was needed. D-glucose powder was measured for 250 ml solution. Table shows the required amount of D-glucose powder in 250 ml of DI water to make different concentration levels. Then the powder is poured into 250 ml DI water and stirred well to mix. 50 mg/dl, 100 mg/dl, 150 mg/dl, 200 mg/dl, 250 mg/dl, 300 mg/dl, 350 mg/dl, 400 mg/dl, 500 mg/dl–these eight different levels of aqueous D-glucose solutions were made.

Concentration Value (mg/dl)	**DI Water (ml)**	**Glucose amount (g)**
50	250	0.125
100	250	0.25
150	250	0.375
200	250	0.5
250	250	0.625
300	250	0.75
350	250	0.875
400	250	1
500	250	1.25

Table 5-1. Appropriate proportion of DI water and Glucose powder for making Aqueous glucose Sample solution

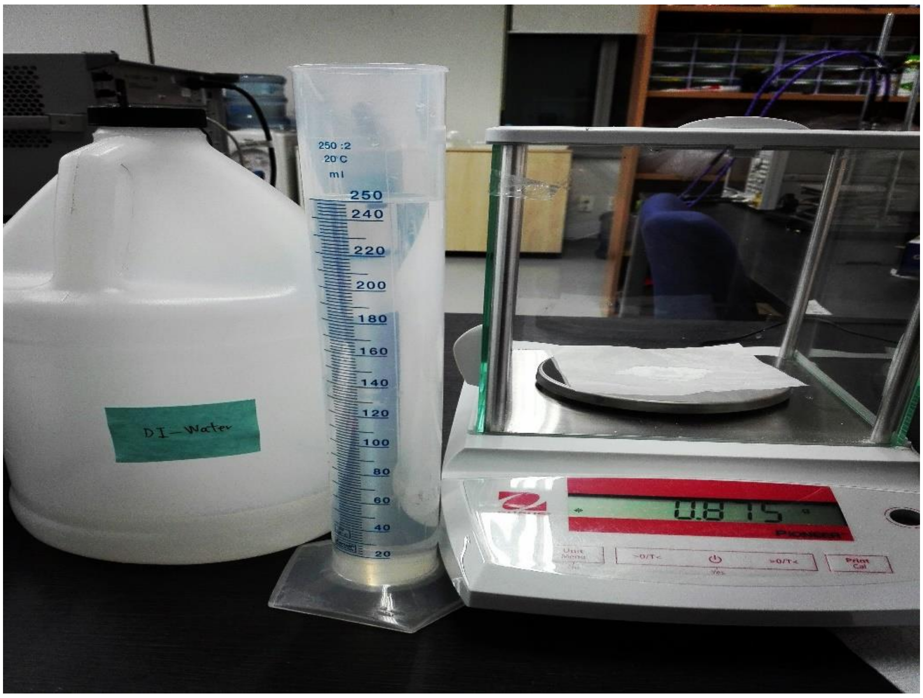


Figure 5-1. Measuring 250 ml DI water and appropriate amount of D-glucose powder for aqueous solution

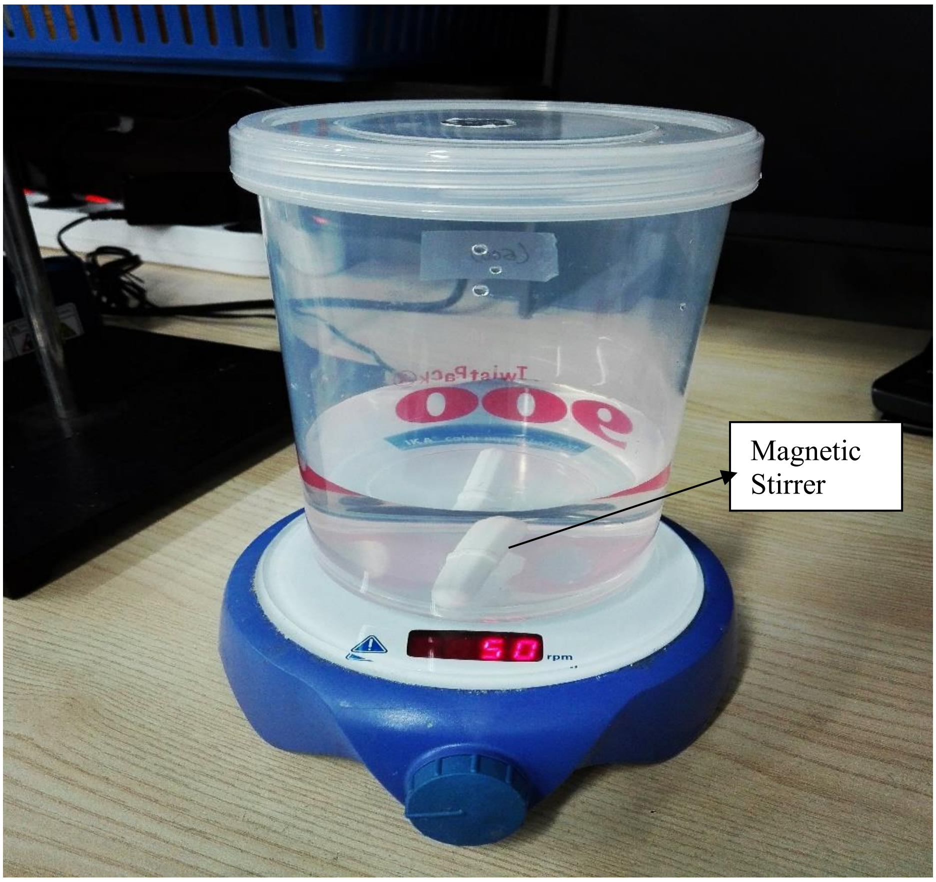


Figure 5-2. Stirring the solution

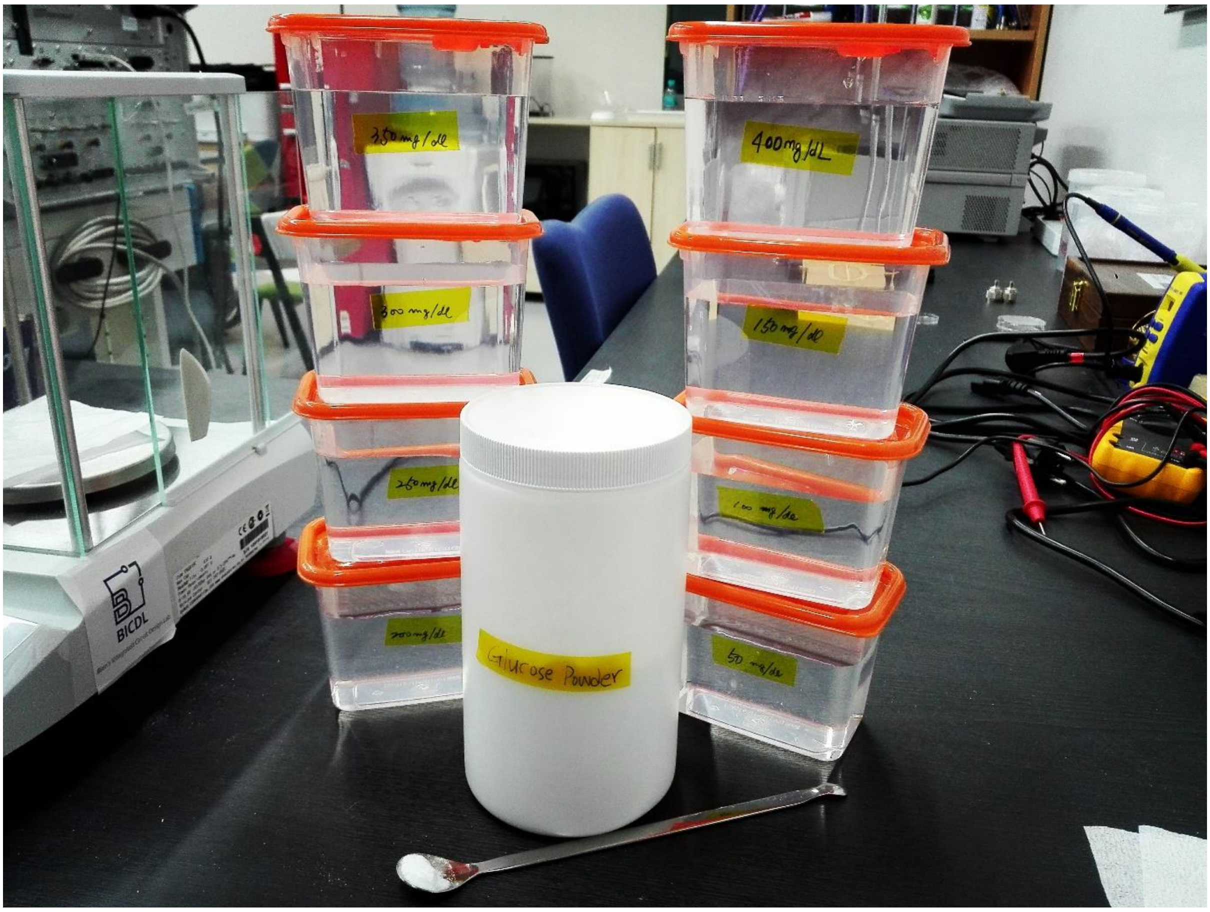


Figure 5-3. Different Aqueous glucose solutions

5.2 Experimental set up

A plastic container of 10ml volume and a glass beaker of 50 ml volume were used to hold the sample solutions. Glucose concentration has a very high dielectric constant which means it interacts with the electromagnetic field very strongly compared to other materials. Based on this property, the transmission co-efficient was checked to observe the shift in S parameter. The change in resonant frequency is dependent on the mean radius of the resonator. A Network Analyzer was used to measure the S21 parameter and the resonant frequency. The operating frequency was observed near $f = 2$GHz. The experiments are conducted at 25℃ temperature.

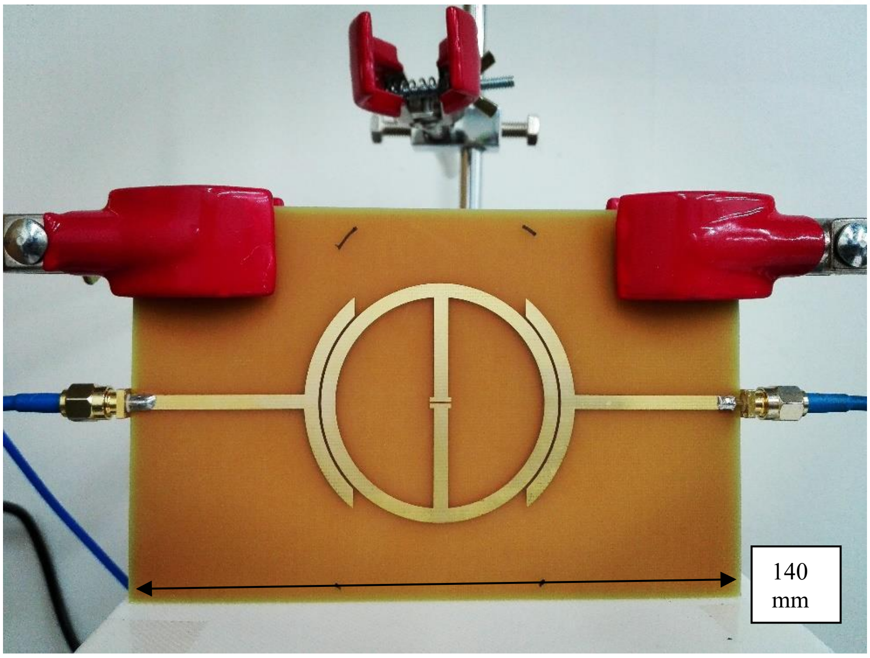


Figure 5-4 Fabricated Ring Resonator.

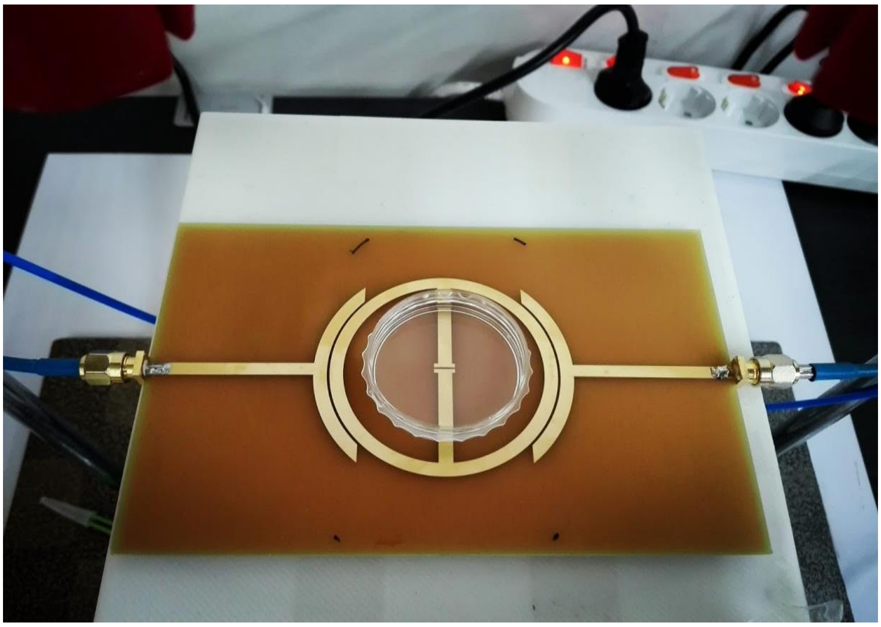


Figure 5-5. Experimental Setup; The sample solution is taken in a circular shaped plastic container and placed on the ring resonator

5.3 Results and Discussions

Figure 5-6 shows the microwave transmission coefficient S_{21} profiles of different aqueous glucose concentration level ranging from No load to 500 mg/dl. The glucose concentration volume was10 ml. With the change in glucose concentration, the dielectric permittivity changes and so the transmission co-efficient S_{21}changes. Table 5-2 contains the experimental values showed in figure 5-6. From the data it is easily observed that the resonant frequency has shifted 3 MHz each time the concentration changed.

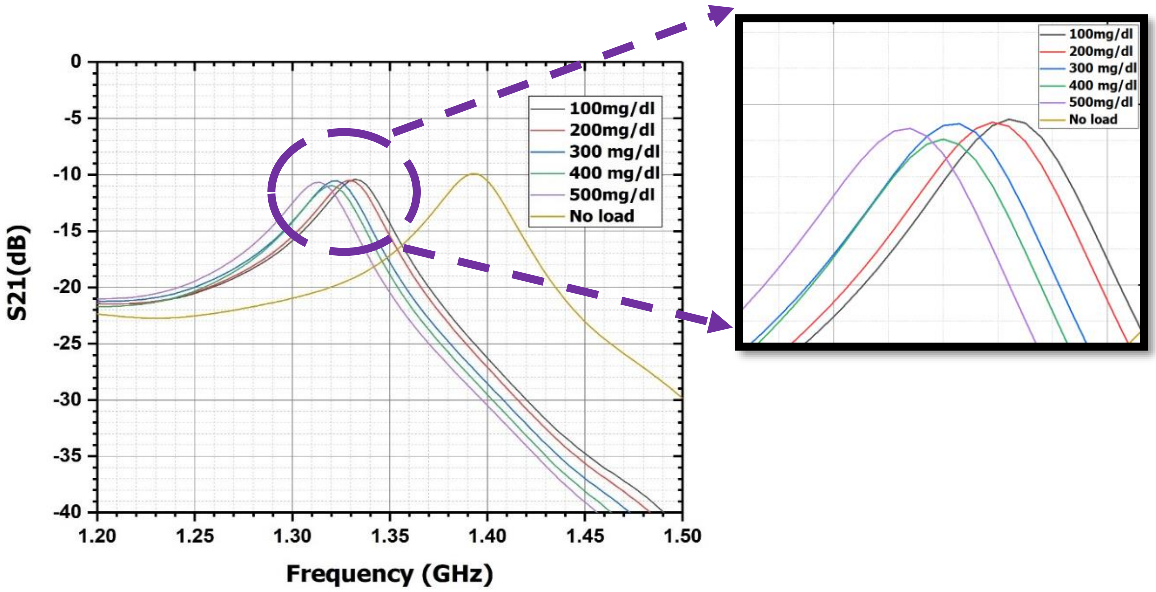


Figure 5-6. Experimental Result for different concentration level of aqueous glucose (100 mg/dl interval)

Aqueous glucose Conc. Level (mg/dl)	Resonant Frequency (GHz)	S21(dB)
Without load	3.392	-9.9824
100	1.332	-10.401
200	1.329	-10.491
300	1.323	-10.529
400	1.320	-10.927
500	1.327	-10.945

Table 5-2. Traced data for S21 parameter and frequency shift for 100 mg/dl change in concentration

In figure 5-7, the experiment follows the same procedure as stated above. The main difference is, in this case the interval was 50 mg/dl instead of 100 mg/dl up to 400 mg/dl. Data shown for this measurement in table 5-3, depicts almost 1 MHz shift for different level of concentration

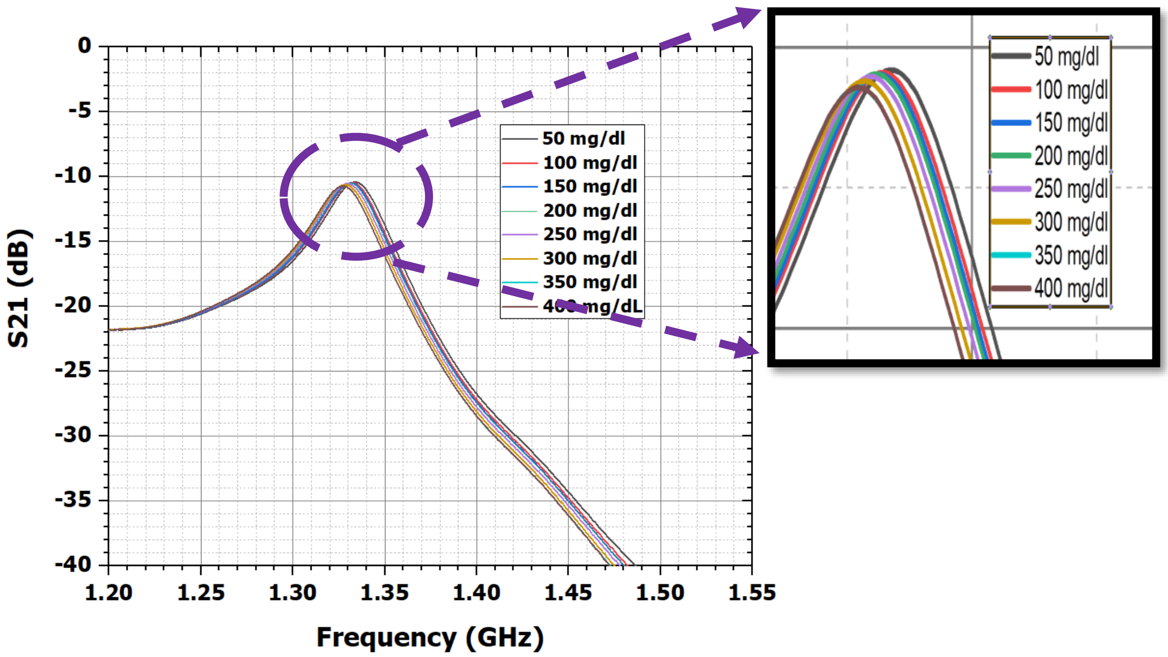


Figure 5-7. Experimental Result for different concentration level of aqueous glucose (50 mg/dl interval), inset a zoom in for the peaks are presented which clearly shows 1MHz shift.

Aqueous glucose Conc. Level (mg/dl)	Resonant Frequency (GHz)	S21(dB)
50	1.333	-10.413
100	1.332	-10.459
150	1.331	-10.484
200	1.330	-10.483
250	1.329	-10.528
300	1.328	-10.609
350	1.327	-10.725
400	1.326	-10.720

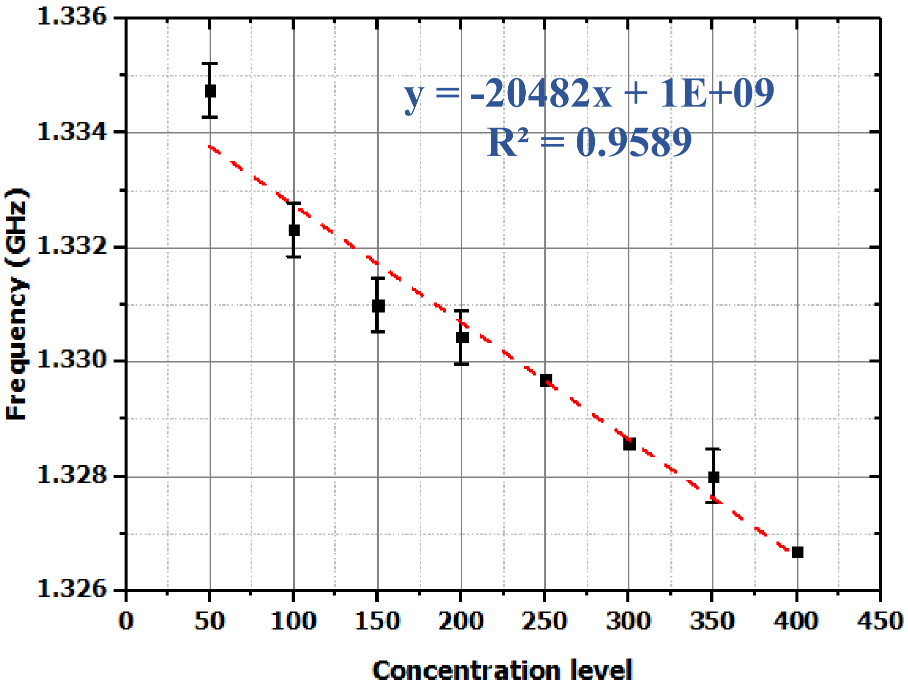
Table 5-3. Traced data for S21 parameter and frequency shift for 50 mg/dl change in concentration

We continuously repeated the experiments 1 and two to check the errors and reproducibility of the results. In graph 1 for 50 mg/dl we see slope value is 20 KHz, which implies the validity of 1MHz shift. In graph 2 there is some error for 300 and 400 mg/dl. Still data 94% data fitted and little more than 30 KHz slope value indicates data reproducibility.

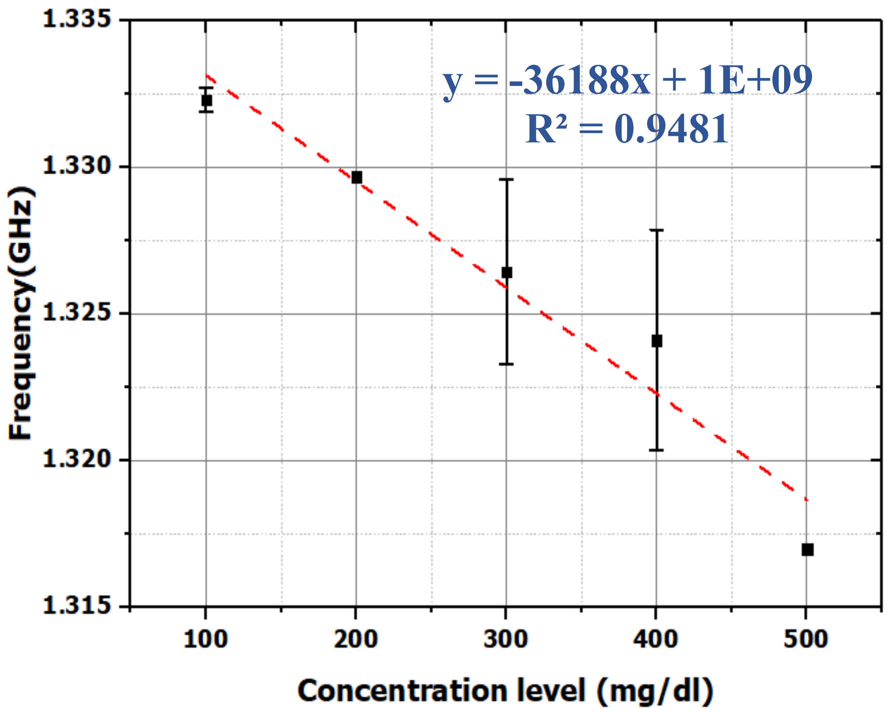
Apparently, 100 mg/dl data interval has some differences with 50 mg/dl data interval. Practically, both follow the same trend. As we place a sample the value of the C_v practically varies nonlinearly. The frequency also varies nonlinearly. This C_v and frequency relationship is understandable from the equation of angular frequency explained in previous chapter.

We plotted the data for curve fitting to analyse the trend mapping. Both the graphs follow the same trend. The trend is more understandable when the interval is decreased.

From the error bars we can see in 100 mg/dl interval and 50 mg/dl errors are not all the same for the same concentration levels. It is due to the experimental limitations. Wastage of the sample, evaporation of the sample, temperature effects, placement offset of the sample on sensor etc. can influence to have inappropriate results. Dryness of the sensing part of the resonator and container is also important as it may show different results if these are wet. For these reasons, it is better to change the solution time to time for a set of experiments.



(a)



(b)

Figure 5-8. (a) Error bar and curve fitting analysis for 50 mg/dl interval, **(b)** Error bar and curve fitting analysis for 100 mg/dl interval

For data reliability an experiment for different liquid compositions (i.e. cola, energy drink, mango juice and natural tap water) was conducted. The cola contains carbonated water with sugar, color, phosphoric acid some natural flavors, the energy drink is composed of different ions such as Na^{+}, Ka^{+}, Ca^{++}, Mg^{++}, Cl^{-}, Citric acid and sugar. Juice contains mango pulp, citric acid, artificial flavor, ascorbic acid and most importantly sugar. All the samples have sugar in common. In the experiment 10 ml of each solution was taken. There was distinguishable change in frequency due to the change in sample. Clearly these values are different than the previously reported results for various aqueous glucose solution concentration level. This is a proof that the proposed ring resonator can distinguish among various concentration level of sugary sample of any composition.

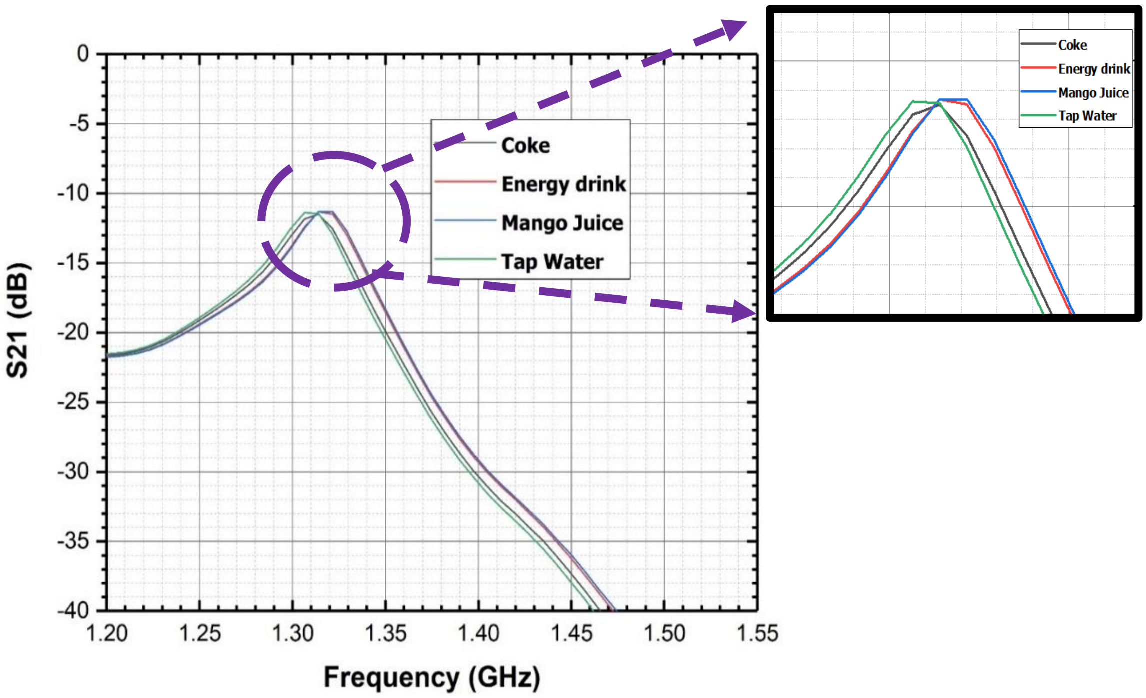


Figure 5-9. Experiment for different sugary sample

We also observed the temperature dependency of the glucose solutions. The measurements at 25° C and 33° C are not the same. We chose 33° as in general condition the body temperature is between 33° -35° C.

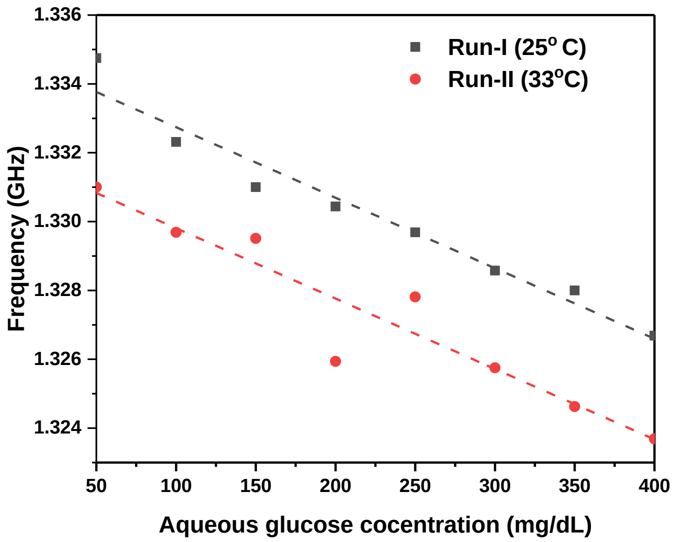


Figure 5-10 Temperature Effect

Temperature effects the dielectric constant and hence the measured data shift from the estimated values noted before for different aqueous glucose concentration level.

Chapter 6

Conclusion and Future Work

The results show a great feasibility of the microstrip ring resonator for the research in glucose sensors. Further research would be helpful to explore and find more solutions for the challenges faced. The proposed sensor has improved sensitivity and Q factor than the loosely coupled ring resonators. It has simple circuitry therefore easy for circuit integration.

Further research on the proposed sensor is going on to implement it as an external sensor. We are going to test with blood sample and comparing the result with the available glucose sensors. Modification of the geometry such as shorter microstrip length will lessen 50% of the overall sensor size. Substrate with higher dielectric constant will improve sensor performance. Currently we are focusing on the flexible design to attach on the arm. With the mapping of the trends of frequency shifting we are planning for algorithms that can be helpful for continuous measurements.

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